RESEARCH PROGRESS AND NEEDS
CONSERVATION TILLAGE

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A North Central Region, Agricultural Research Service, U.S. Department of Agriculture soil tillage research workshop was held in Council Bluffs, Iowa, January 6-7, 1976. As a result of the discussions, the enclosed state of the art papers were prepared.

The purpose of this publication is to present an account of research needs in the field of soil tillage in the North Central Region.

Mention of companies or commercial products does not imply recommendation nor endorsement by the U.S. Department of Agriculture over others not mentioned.

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RESIDUE MANAGEMENT AND PHYTOTOXIC SUBSTANCES

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NATURE, SCOPE, AND SEVERITY

Recent economic and environmental concerns have placed many new burdens upon agricultural production and research. Crop production systems are needed that will maximize yields with concurrent conservation of soil, water, mineral, and energy resources, and environmental quality. One production system, which incorporates all of the aforementioned factors, is minimum tillage combined with crop residue management. The addition of crop residues, with minimum incorporation into soil, often results in decreased crop yields. With stubble-mulch tillage, such yield reductions have resulted from the production of phytotoxic compounds, which were stimulated by crop residue additions.

Phytotoxic substances can be produced from crop residues in three ways. First, phytotoxic substances can be released directly from the residue as it stands in the field. Much research has shown that the addition of many crop residues to the soil results in the release of both gaseous and water-soluble products, which can inhibit either plant growth or microorganisms that are important to nutrient cycling. Second, surface addition of crop residues also results in a stimulation of selected microorganisms, which, in turn, produce phytotoxic substances. The addition of large quantities of organic matter to soil shifts the balance of microbial populations and results in predominance of those organisms which can most readily utilize the added material. Third, the addition of crop residues to soil can result in a stimulation of microorganisms which are, themselves, pathogenic to the crop being grown. Mulching of the soil surface changes the microclimate and can result in an increase in plant disease due to insect and microbial infestations.

The addition of certain crop residues to soil also can result in decreased yields through interruption of the cycling nutrients in soil. Although this is not a direct phytotoxic effect, the final result in decreased yields is the same. The addition of plant residue to soil, with minimum incorporation, leads to localized stimulation of microbial activity and development of anaerobic conditions. Such pronounced changes in the soil will invariably effect such important biological processes that control the availability of carbon or nitrogen as mineralization, immobilization, nitrification, and denitrification. The availability and transformations of other elements will also be altered by surface residue applications.

Maximum use of the benefits offered by conservation production systems, namely, reduction of wind and water erosion and conservation of water and mineral resources, will come only with widespread acceptance and use. Acceptance of these production systems will result when the factors responsible for inconsistent crop yields are determined and corrected.

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PAST AND PRESENT RESEARCH

Most of the past research pertaining to the effects of crop residues on crop yields has been conducted by McCalla and his colleagues in the U.S. Department of Agriculture Agricultural Research Service and the University of Nebraska and by Patrick and his colleagues in the Canada Department of Agriculture. The research from these two groups has concentrated on studying phytotoxicity produced directly from residue or from production of phytotoxic substances by microorganisms stimulated by residue application. Excellent reviews of crop residue and phytotoxicity have been made by McCalla and Norstadt (1974) and Rice (1974).

The addition of many crop residues to soil results in the release of both water-soluble and gaseous products which can inhibit plant growth. Most crop residues contain water-soluble substances that have been shown to inhibit the growth of wheat, corn, sorghum, soybeans, oats, tobacco, timothy, and alfalfa (Guenzi and McCalla, 1962; McCalla and Duley, 1948; Nielsen and others, 1960; Patrick and others, 1963). Guenzi and McCalla (1966) have identified and quantified five phenolic acids isolated from plant residues of oats, wheat, sorghum, and corn as being water-soluble compounds inhibitory to growth of wheat seedlings. Patrick (1971) identified fatty acids as well as phenolic acids as phytotoxic compounds associated with decomposing rye residues. Phytotoxins are broken down fairly rapidly in soil (Patrick and others, 1964) and, consequently, growth inhibition from phytotoxic substances is greatly dependent upon the degree of decomposition of the plant residues in the soil (Guenzi and others, 1967).

Along with water-soluble products, many volatile compounds are released from plant residues that also have a profound effect upon plant growth. Ethylene, a gas produced by both plants and microorganisms, is known to retard Robertson, 1971; Burford, 1976). The phytotoxic effect of volatile compounds released into soil is often indirect in that the volatile compounds directly affect microbial activities, which, in turn, are important to plant growth. Work done at Beltsville has shown that volatile aldehydes and alcohols, produced when many plant residues are added to soil, have been found to selectively stimulate (Menzies and Gilbert, 1967; Owens and others, 1969) or suppress (Gilbert and others, 1969) bacterial or fungal populations. Other investigators at Beltsville have demonstrated that certain plant pathogens can be both stimulated and inhibited by volatiles released from plant residues (Gilbert and Griebel, 1969; Papavizas and Lewis, 1970). Bremner and Bundy (1974) found that the decomposition of sulfur-containing plant residues results in the formation of volatile organic sulfur compounds, which retard nitrification in soil.

Crop production systems that leave a large quantity of residue on the soil surface can often lead to decreased yields through stimulation of microbial populations that produce phytotoxic compounds. McCalla and Haskins (1964) indicated that of 318 fungi isolated from soil in stubble-mulched plots at Lincoln, Nebr., 52 of the organisms produced toxins that reduced shoot growth of corn by 50 percent or more, and 167 of the organisms produced toxins that reduced root growth of corn by the same percentage. Norstadt and McCalla (1969) have shown that stubble-mulching of wheat results in a change of the

soil fungal population and, at certain times of the year, produces conditions favorable for growth of a penicillium that produces the phytotoxic compound, patulin. Tillage machinery design and use can be adapted to allow management of crop residues with conservation of soil and water and a minimization of phytotoxicity (Woodruff and others, 1966).

T. M. McCalla and the research group at Lincoln, Nebr., have initiated a multidisciplinary research effort to characterize the physical, chemical, and biological effects of tillage systems, with management of plant and animal residues, upon the soil and plant environment. Major emphasis is being placed of water-soluble or gaseous phytotoxins or compounds, which stimulate or suppress microbial activity and mineral transformations to affect yields of corn and wheat. The Reduced Tillage Management research group at Pullman, Wash., currently is studying the effects of residue management with no-till on the production of phytotoxic compounds. Crops under study are wheat, lentils, and peas. Research emphasis is on if, and when, phytotoxicity occurs. Cooperating in phytotoxicity research with the Pullman group is the Plant Protection Phytochemistry group at the Western Regional Research Center, Albany, Calif. A. C. Waiss has stated that the group at Albany has developed a simple and efficient bioassay for detecting phytotoxin production. Investigations currently are underway to identify two unknown phytotoxic substances which have been isolated from wheat residue from the Palouse area of Washington state.

RESEARCH NEEDS AND APPROACHES

An in-depth understanding of the influence of tillage and residue management systems on the physical, chemical, and biological components of the plant-soil environment will be an essential component in optimizing conservation production systems with crop yield and quality. Unfortunately, because tillage itself is a physical manipulation of the soil, much tillage research has stressed the effects on the physical characteristics of soil; only minor emphasis has been placed upon biological considerations.

Tillage alone can have dramatic effects upon biological equilibria and microbial populations in soil (McCalla, 1967). Reductions in crop yield, associated with conservation production systems, have emphasized the need for a complete understanding of the biological changes in the soil environment. Research to determine the biological effects of minimum tillage and residue management will be multidisciplinary because of the necessity of studying the microbiology, biochemistry, chemistry, and physics of the plant-soil environment, as well as the physiology and disease- and insect-vulnerability of the crop itself.

An important component in the study of conservation production systems should be the characterization of the microbiology of the soil. This aspect should not only involve the correlation of counts of soil fungi, actinomycetes, and bacteria with the conservation production systems. It also should include the effects of tillage and residue incorporation upon microorganisms that are responsible for such agronomically and environmentally important transformations as nitrification and denitrification. In specifically studying the

effects of residue management on production of phytotoxic compounds, the water-soluble and gaseous phytotoxic compounds will have to be identified. In the case where phytotoxic compounds are being produced by microorganisms, the microorganisms responsible for their production will have to be identified. Research relating to production of specific phytotoxins will involve laboratory, greenhouse, and field experiments. In the field, phytotoxicity should be correlated with residue management and minimum- and conventional-tillage treatments. Research at several locations will permit evaluation of how biologically induced phytotoxicity is affected by climate, type of residue, and crop type.

The biological considerations of minimum tillage and residue management should be carried much further than phytotoxic considerations. As stated earlier, the definition of phytotoxicity associated with residue management should include any chemical modification of the soil-plant environment brought on by the application of residues that will have a deleterious effect on plant growth and crop yield. From this consideration, characterizing conservation production systems will be necessary as they influence nutrient transformations and availability. Consequently, analysis of soil and plant tissue under conservation production systems will give a more complete understanding of the effects of residue management on nutrient availability. Determination of the effects of residue management on selected enzyme activities in plants and soil (cellulase, phosphatase, urease, and so forth) will also help determine the effects of residues upon nutrient availability and plant growth.

As stated, to determine the biological effects of residue management on crop yield, observing plants under different tillage and residue management systems in the field during the growing season will be important. This will involve direct participation in tillage research of plant physiologists, plant pathologists, and entomologists. Only through cooperation among many disciplines can a useful understanding of the effects of residue management on the crop be realized.

EXPECTED BENEFITS

An understanding of the basic biological phenomena associated with minimum tillage and residue management will help reduce yield limitations imposed by phytotoxicity. Also, it will lead to a better use of the additional 2 to 6 inches of water that is stored by mulching, which will lead greatly to increased crop yields. The definition of minimum tillage and residue management systems that do not restrict crop yields will lead to widespread acceptance of these conservation production systems. Such systems will result in conservation of soil, water, and nutrients as they are used more extensively in agriculture. Reduction in wind and water erosion of mulched agricultural lands also will lead to an increase in the quality of air and water.

Optimum use of minimum tillage and residue management systems will also yield indirect monetary benefits by overcoming yield reductions, capitalizing on stored water, and reducing tillage. The energy input per unit of crop harvested will be decreased. Also, crop quality will be increased as nutrient composition of the crop is affected and by curtailing of physiological disorders that are imposed by microbial and insect diseases.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE (MODELING)

Only through a complete understanding of the physical, chemical, and biological effects of conservation production systems on the soil and plant environment can predictions be made on how these systems will act in other geographical areas. A basic problem in the development of a model which will be applicable to interregional as well as interdisciplinary research will be the choice of appropriate baseline parameters. How is a model developed that will use both physical and biological data collected in different regions? One answer to this question may be in the choice of dependent variables for which data are available in the literature and are most frequently used in agricultural research endeavors. One example of such a universal "dependent variable" would be crop yield.

Of course, within research disciplines, equations will be developed that are defined by the parameters which are important to each particular area of study. However, it will be important that baseline parametrers (lowest category or variable in an equation or model) should be chosen so that data measurements can be applied and used by other disciplines. Examples of a few such parameters would be soil, temperature, air, or water content. These soil parameters are affected by physical properties of soil and have direct influences upon the chemical and biological components of the soil-plant environment.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

A delineation of the effects of minimum tillage systems with residue management upon soil biological systems will necessitate the inclusion of a soil microbiologist, a microbiologist, a biochemist, and a soil chemist at one or more locations. To assess the effect of changes in plant growth and quality brought about by residue management and tillage operations, the plant from germination through harvest should be studied closely. Such studies will require the inclusion of a plant physiologist, a plant pathologist, and an entomologist in the total research package. Such a comprehensive research effort to determine the phytotoxic effects of tillage and residue management systems on crop yield and quality would require all of the aforementioned personnel. To use the data from such a research endeavor in a predictive sense (model) would require a duration of study of at least 5 years.

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RANDOM ROUGHNESS AND MACROPOROSITY IN TILLAGE SYSTEMS AND THEIR INFLUENCE ON SOIL ENVIRONMENT

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Many characteristics of a tilled layer influence soil environment, which, in turn, mediate plant response to tillage inputs. Among these factors are random roughness and macroporosity. Other factors include surface residue amount and distribution on the surface and soil compaction. Random roughness and macroporosity are measured readily with a microrelief meter (grid of surface height measurements), transit, and undisturbed cores in a manner discussed by Burwell and others (1963) and Allmaras and others (1966). Other methods of measuring random roughness and macroporosity were developed by Kuipers (1957) and Currence and Lovely (1971)--both using the same principle as Burwell and others (1963).

These two parameters describe soil fabric features that exert quantitative influences on soil environment, but these relations are not summarized in a form readily used in a tillage guide. Once relations are developed between random roughness (macroporosity) and soil environment, one can use predicted soil environment effects as inputs to a plant modeling scheme for predicting crop response to tillage. There are also more direct effects of random roughness (macroporosity) on wind and water erosion--these are also amendable to modeling by use of the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation.

The feasibility of relating soil environment to the random roughness and macroporosity soil structure parameters prompts a reexamination of a) the uniqueness of random roughness (macroporosity) in relation to soil type, tillage implement, moisture content, and bulk density; and b) relationships that can be developed between random roughness (macroporosity) and soil environments of water intake, redistribution, evaporation, thermal properties, and erosion. This conference report briefly proposes approaches toward development of tillage guides for random roughness and macroporosity.

Random roughness is highly correlated with macroporosity, but yet a formal relationship has not been developed. It is suggested that a plot of fractional porosity (ordinate) versus random roughness (abscissa) will produce a threshold fractional porosity and random roughness above which there will be a positive correlation. Such information could be developed from tests conducted from 1962 through 1970 on Kranzburg, Barnes-Aastad, and Nicollet-Webster soil series. In some tests, there is also associated information considered on inter- and intra-aggregate porosity fractions. R. E. Burwell has also developed some unpublished calibration relations of random roughness and corresponding photographs. I can also develop some of these same pictorial relations.

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Research in Minnesota during 1962-70 developed considerable information about random roughness (and porosity changes) produced by moldboard plowing. This information is summarized as follows (Allmaras and others, 1967):

a) Typical ranges of random roughness and fractional porosity occurred for plow, plow-disk-harrow, plow and wheel-pack, each as a separate group.

b) Random roughness decreased with increased initial porosity but porosity increase from plowing showed little relation to initial porosity.

c) Random roughness from plowing as a function of tillage-time water content was a minimum at the lower plastic limit (LPL) and increased as soil water content decreased or increased. Porosity increase became markedly greater as soil water content was decreased below the LPL.

d) Disking operations on freshly plowed surfaces usually decreased porosity, but, in the Kranzburg soil, disking had little influence. Meanwhile, random roughness was always decreased.

Little corresponding data on random roughness and fractional porosity (macro) exists outside the Mollisols of Minnesota. However, Lyles and Woodruff (1961, 1962) have done similar work in Kansas. Also this work can be generalized based on the single tool-soil consistency models discussed by Spoor (1975).

In terms of plant needs, currently available research can be used to project effects of random roughness (and macroporosity) on water intake before runoff, evaporation from bare soil, runoff itself, thermal properties of soil, and water redistribution in soil. Separate effects on wind and water erosion can be predicted. Random roughness and porosity showed a good relation to water intake before runoff, but after runoff began, these parameters were no longer closely related to water intake rate (Burwell and others, 1967; Burwell and Larson, 1969). Based on cumulative rainfall energy inputs before runoff, these same studies showed the approximate value of random roughness and macroporosity in deterring runoff during the sensitive early spring erosion in the Corn Belt. Probabilities of cumulative rainfall equal to or less than expected infiltration for a given random roughness for a time period could be used to show probabilities for potential infiltration or soil stored water. The cropping factor (C) values to display soil erosion deterrents by random roughness and macroporosity in the USLE could be obtained from the Wischmeier studies where there were comparisons of tillage systems. Such information is available in Morris studies on erosion.

Soil type, slope, and water application characteristics were fixed variables in the Burwell and Larson (1969) studies, but associated studies can be used to extend these runoff and infiltration relations to other rainfall rates (even intermittent rainfall). Slope effects can perhaps be accounted for by using a surface detention model to extrapolate "water intakes before runoff" to slopes greater or less than the 4 percent used in the Burwell and Larson (1969) studies. Soil type effects can perhaps be estimated in the following

manner: Final infiltration rates are known on many soils of the Corn Belt as a result of the rainulator studies and can be approximated by $I = at^b$ curves where t is time after incipient ponding or runoff production and I is cumulative infiltration. In plots of cumulative infiltration versus applied water (R. E. Burwell, unpublished), the curves after initial runoff are parallel and more displaced to the right as the intake increases before runoff. This is logical, because after initial runoff, random roughness and macroporosity were no longer controlling intake. Assuming that infiltration just after initial runoff characterizes infiltration during the period before runoff, the water intakes before runoff can be adjusted to account for the different infiltration rates just after runoff begins. When this is done for the Nicollet and Barnes soils of the Burwell and Larson (1969) study, the water intakes before runoff are more closely related to the measured random roughness observations. This argument can be developed further to give projected random roughness versus water intake for soils of different final infiltration rates. We have final infiltration rates of 0.3 cm/hr compared to 3.8 cm/hr for the Barnes soil in the Burwell and Larson (1969) studies--maybe this is why random roughness has less value for runoff control in the Pacific Northwest.

Daily evaporation form bare tilled surfaces ranged from 0.85 of potential evaporation the first day after a 2-cm rain down to 0.3 of potential five days after the rainfall (Allmaras and others, 1977). Meanwhile, the plow treatment (maximum random roughness and porosity) showed a greater evaporation that was also about 17 percent of potential--gradually this difference among tillage treatments diminished to <6 percent of potential evaporation. Apparently subsoil moisture has less effect than random roughness on evaporation. Based on these data and intermittent rainfall, one can develop an evaporation estimate for differences in random roughness and macroporosity. The enhanced evaporation on the greater randomly rough soil is based on enhanced turbulent exchange. One can readily see that intake is the far more important factor during early summer in the Corn Belt.

These same studies provide ample background to predict soil temperature characteristics as a function of random roughness and macroporosity. Thermal conductivity of tilled layers (a composite of turbulent and diffusive components) was related to random roughness and macroporosity and to the diffusive thermal conductivity predicted by de Vries analog. Random roughness also showed an influence on turbulence within 50 cm of the soil surface--an inflated heat transfer coefficient was noted and could be calculated. These observations could help in more accurately predicting thermal properties (heat conduction, amplitudes of soil temperature, influences of tillage layers on heat flow, frost danger) produced by random roughness and macroporosity changes.

In the Allmaras and others (1972 and 1977) studies, there was a negative relation between random roughness and surface albedo which, in turn, affects overwinter soil temperatures. Soil temperature influences can be shown on subsequent corn growth and timeliness of secondary spring tillage and planting. The random roughness effect on surface albedo can be explained on the basis of surface shading, incident angle of direct beam, and radiation scatter. It suggests that random roughness could be determined by densiometer scanning for

light and dark areas on photographs of the soil surface taken in a series (as a function of sun angle) and with fixed camera position. In the Allmaras and others (1972) study, a simplified model was used to give soil inclination angles as a function of random roughness index. For the tillage guide, these radiation interception versus random roughness effects can be used to project differences of average soil temperature which, in turn, relates to seedbed temperatures and root environment temperatures if the surface is exposed to radiation over long periods during low sun angle.

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TILLAGE AND SOIL WATER

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Severe limitations on growing agronomic crops in the North Central Region of the United States are water erosion, wind erosion, and the loss of water needed for crop growth through runoff from severe storms or the loss of water through evaporation directly from the soil surface. All of these factors are controllable to some extent by the type and timeliness of tillage methods used during the course of the year in growing a particular crop. Although wind erosion is a serious problem throughout the region, both from a soil depletion standpoint and from an air pollution standpoint, this paper will address mostly water erosion and unnecessary water losses, to the extent they can be controlled by tillage without severely lessening the yields obtainable from crops, and for the most part, it will be restricted to row crops as opposed to solidly planted small grain.

Lemon (1956) discusses the potential for decreasing soil water evaporation loss by tillage. He has listed two ways that tillage can influence evaporation loss of water from soil: (1) decreasing the turbulent transfer of water vapor above the ground surface, and (2) decreasing the capillary conductance of water to the surface by decreasing capillary continuity. The objective of a good tillage system in most of the North Central Region is to maximize the net storage of water received from rainfall while maintaining the best possible environment for plant growth. This means manipulating a soil surface so that it is receptive to water infiltration from the rainfall received in the early and precrop portion of the year in excess of immediate needs and storing this water in the soil profile for future crop needs.

In most of the North Central Region, rainfall distribution is such that the large part of the rainfall comes after harvest and before planting and must be stored in the soil profile for subsequent plant use. Much of this precipitation comes through high-intensity rainstorms of short duration. A further complicating factor is that some of these rains occur when the soil is frozen or when the surface is saturated and the underlying soil is frozen. These periods must be kept in mind because of the high erosive nature of this situation that can be altered by tillage or timeliness of tillage.

PAST AND PRESENT RESEARCH

The effect of various tillage methods on rainfall infiltration has been studied extensively by several workers at the USDA Soil Conservation Research Center, Morris, Minn. (Burwell and Larson, 1969; Burwell, Sloneker, and Nelson, 1968) and at Purdue University, Lafayette, Ind. (Mannering, Meyer, and Johnson, 1966; Meyer and Mannering, 1961) as well as at other locations. The

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purpose of this research work was to determine the effect of tillage methods on the infiltrability of the soil. The general concensus from this research was that soils with an open cloddy surface protected with some residue offered the possibility of the greatest infiltration, thus tillage leaving the soil rough and open is desirable during that part of the year when rainfall is greatest and evaporation demand is still low.

Getting the greatest net storage of water for growing crops requires that infiltration, evaporation from the soil surface, and drainage from the profile be taken into account. The drainage component in soils without a water table is important and limits amount of storable water, but very little that is technically or economically feasible can be done to influence it except in very special situations involving high economic return crops. Erickson (1972) has used various barriers under sandy soils in Michigan to increase their water-holding capacities, but this practice is very limited to small specialized areas of application.

Evaporation from the soil surface and transpiration from weeds and volunteer (unwanted) crop plants accounts for much of the losses of water from the soil profile. Stored soil water actually used by growing agronomic crops represents a net saving after accounting for infiltration, evaporation, unwanted transpiration, and water movement into and out of the root zone. Several workers have measured water use by crops using stored water (Holt and Van Doren, 1961; Holt, Timmons, Voorhees, and Van Doren, 1964; Holt and Timmons, 1968; Timmons and Holt, 1968; Olson and Schoeberl, 1970; and others), and some work has been done to measure the effect of tillage on evaporation rates of water from soils (Allmaras, 1967; and others) as affected by surface conditions left by various tillage operations. The influence of surface residues on evaporation is confounded with the influence of soil conditions in making evaporation measurements, but these measurements are valuable because the effect of tillage is often caused by a combination of soil conditions and residue left and distributed on the surface.

RESEARCH NEEDS AND APPROACHES

Most field research in tillage has been to compare various tillage practices to what is called "conventional" tillage with resepect to early plant growth, yield, or water use efficiency, or a combination of these. Some of the workers mentioned before have attempted to characterize tilled soil surface layers in terms of roughness, aggregate size distribution, and porosity and to relate these characteristics to plant growth, water accumulation, or soil temperatures. However, there has been little success in integrating this specialized knowledge and these measurements of tillage effects into a tillage guide that will enable technicians, farm operators, or machinery designers to use the literature as a sound basis for developing a tillage system or a tillage machine.

A tillage guide must take into account rainfall distribution, time distribution of potential evaporation rates, erosion characteristics of the soil, and water flow characteristics of different soils. Water flow theory can give guidelines on the effect of tillage on movement of water into and

from the soil. However, more research is needed on the flow through layered soil and on the relative flow resistances of the plant and soil so that water flow through the soil-plant system is better understood than is presently the case. Hard-to-measure flow characteristics such as conductivity and water pressure must be correlated with more easily measured parameters such as soil texture, total potential evaporation, plant leaf surface, or others so that simple application of flow theory can be used by the technician. The first approximation of any tillage guide may have to treat water flow in the soil profile in very elementary ways to get a framework in which to build a model that will identify further research needs.

RESEARCH APPROACH TO BUILDING A TILLAGE GUIDE FOR THE NORTH CENTRAL REGION

The Soil Conservation Service (SCS) and the Extension Service (ES) will be prime users of any general tillage guide that is developed. These agencies look to ARS for research results that they can use in advising individual farm operators and others what tillage method to use. Many aspects of tillage must be considered in advising user clients in growing operations. The SCS is presently using ARS-developed methods to determine what crops can be grown that will hold soil erosion to predetermined maximums. The method involving water erosion was developed using what is termed the Universal Soil Loss Equation (USLE). The question of erosion is so important and the use of the above erosion equation is so entrenched in SCS practice that any tillage guide must build on the erosion equation concept. The USLE (Wischmeier and Smith, 1965) consisting of several multiplicative factors is as follows:

$$A = RKLSCP$$

where A is the computed soil loss per unit area
R is the rainfall factor
K, the soil erodibility factor, is the erosion rate per unit of erosion index for a specific soil in <u>cultivated continuous fallow</u>
L and S are factors for length and steepness of slope.

The first four independent factors are fixed for a particular location, but the remaining two are not. The "C" factor is the cropping management factor and is defined as "the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated." The "P" factor is called the erosion-control practice such as strip-cropping, terracing, or contouring that is used on the particular field in question.

In practice, the SCS and the various state experiment stations have established soil-loss tolerances by soil type and location. These tolerances establish the maximum average annual soil loss that can be permitted from any particular soil type. Once this tolerance is established, the product CP can be determined from:

$$CP = \frac{T}{RKLS}$$

where T is the soil loss tolerance for a particular location. The "P" factor has been determined for specific practices, and this factor could be modified to reflect different tillage practices. A more satisfactory procedure would be to determine "P" as is presently done and include modification from different tillage methods in the cropping-management factor ("C"), which is presently calculated for a particular crop rotation by assigning values to time segments of the rotation and combining these segments into a composite factor for the total crop rotation time.

Since this method of predicting erosion losses is in use by the SCS and will continue to be the <u>primary</u> restraint on cropping practice, any tillage recommendations will have to be made with this constraint in mind. Given a value of the "C" factor from the above considerations, a time sequence of tillage operations can be developed with many degrees of freedom to modify the soil and still produce a "C" value within the allotted value.

At this point, a decision would have to be made regarding the aspect of tillage that was most important. Probably, for most of the North Central Region, the decision would be to maximize the net water storage in the soil profile. This would involve working with rainfall distribution, average potential evaporation distribution, and tillage-induced soil surface layer characteristics that influence infiltration and evaporation rates. A first approach would be to work with types of tillage producing an open soil with high infiltration characteristics to be used when rainfall probability for the specific area exceeded evaporation, then switch to a closed soil surface with low evaporation characteristics when evaporation potential was high and rainfall low. This crude approach would be modified by <u>modeling</u> techniques using models that accounted for the several factors involved in net water storage. After alternative tillage systems were evolved that maximized water storage, considerations could be given to other such aspects of tillage as soil temperature for seedlings, insects, diseases, and so forth. A general model incorporating as many of these aspects as possible would be necessary to determine the optimum tillage system for a particular location. This research approach is summarized as follows:

1. Determine "C" value for the particular location using the USLE or erosion equation in use by SCS.

2. Maximize the net soil water storage considering probable rainfall distribution, potential evaporation distribution, and tillage-induced soil characteristics.

3. Optimize other tillage-related aspects as root temperature, soil crusting, and insect control from alternate tillage sequences produced by steps 1 and 2.

4. Develop model for making these maximizations and optimizations.

5. Use model to pinpoint further specific research needs in tillage or tillage-related fields where solutions would help in making the model more accurate.

EXPECTED BENEFITS

Most tillage research in the North Central Region has as its objective the reduction of tillage operations so soil and water can be conserved. This may or may not mean greater yields, but the main objective is to use conservation tillage methods that result in yields at least as good as from conventional methods of farming. The main benefits of conservation tillage are the control of erosion that is a great source of pollution and to reduce the total amount of energy required to grow a crop. Each year in the Corn Belt, many tons of dust are scattered over the landscape and towns and villages leaving a dirty film on houses, sidewalks, and winter snows that results in an unpleasant appearance through several months of each year. Conservation tillage generally applied would eliminate this unsightly condition. Benefits from conservation tillage methods generated from tillage research would be to reduce pollution from erosion and increase esthetic values by eliminating unsightly blowing dust. Large savings in energy required to raise crops would be realized and increased yields would result as a result of improved water conservation.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

A model developed along the lines mentioned above would be applicable to any location growing tilled crops. Localized inputs would be needed to yield specific tillage requirements, but such a model would serve to channel research efforts and data gathering in a direction where results would be directly applicable in improving the model.

The potential for developing and for using such a model is great. Much of the machinery for applying a predictive model in tillage is already available through the SCS and the ES. Such a model would fill a great need.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

Minimuim requirements for developing the model would be for one scientist knowledgeable in the general fields of tillage, soil and microclimate physics, crop production, and statistics or mathematics to bring together existing data and to develop the model based on that data. This scientist would need a staff to assist in gathering and standardizing existing data. Research projects on tillage systems designed to fill gaps in existing information will also be needed on a continuing basis. Other research scientists would be needed to generate data needed by the model and not presently available and to upgrade presently existing data.

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SOIL TEMPERATURE AND TILLAGE

W. O. Willis[1/]

Soil temperature has a major influence on plant growth, and discussions relating to practicality must invariably turn to "cause and effect." Tillage causes changes in soil temperature, surface residue, soil water infiltration, and evaporation. These factors are interrelated and when coupled with growth and yield of a particular crop, the system becomes additively complex (Willis and Amemiya, 1973; Willis and Power, 1975).

The various reasons for tilling agricultural lands can be generally categorized as follows: (a) to establish a soil surface that prevents water and wind erosion, thus conserves soil and water; (b) to manipulate plant residues; (c) to manage water; (d) to prepare a seedbed; or (e) to control weeds. How tillage affects soil temperature depends on the type of tillage and time of year.

Soil temperature is affected by many other factors, including air temperature; type, amount, and duration of radiation; precipitation; soil water content and evaporation; soil texture, structure, color, and thermal conductivity; soil surface aspect; and type and amount of soil cover.

Soil temperature is dynamic and it is difficult to describe fully the soil temperature profile in terms of depth and time. Also, attempts to establish simple linear relations between yield and weather components have been disappointing partly because to apply results from controlled conditions to field situations is difficult.

Reports indicate that mean annual air temperature decreases approximately 2.7°F per 1,000 feet elevation, that daily fluctuations in soil temperature are fairly well damped out at about the 24-inch depth, and that annual soil temperatures are damped at depths below about 30 feet. Temperatures of a south-facing slope will fluctuate less from the annual mean than those of a north-facing slope, and the mean temperature of a north-facing slope is approximately 5°F lower than that of a south-facing slope. The summer temperature gradient is about 1°F per 4 inches of soil depth, and the mean summer temperature at the 24-inch depth is as much as 10°F higher in a cultivated soil than in a forested soil.

SNOW COVER AND COLD TEMPERATURES

The soil-temperature regime during the growing season can be conditioned by antecedent soil water effects and snow cover during the preceding fall and winter. For example, a dry soil freezes quicker and deeper than a wet soil and thaws quicker in the spring. This behavior reflects the higher thermal conductivity and heat capacity of wet soil as compared to dry soil. Also, frost

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depth is reduced about 1 foot for each foot of undisturbed snow cover and, in some instances, as much as 2 feet in frost penetration for each foot of snow. Observations of snowpacks created by tree windbreaks or snow fences at Mandan, N. Dak., have indicated that if a snowdrift is more than about 4 feet deep, the soil under the snowdrift is not likely to be frozen.

In an area with a fairly high water table, and as the profile cools or warms, the water table drops or rises because a cold soil holds more water than a warm soil. The water table will rise in the spring even though frost remains in the upper profile. This indicates the frost mass has changed sufficiently to allow some permeation of liquid flow. Thus, if that frost remains in the profile for a significant time after the surface has thawed and with spring planting, plant roots must grow into soil colder than the surface.

Another factor affecting depth and longevity of snowpack is the type and amount of vegetative cover. For example, with different heights of standing wheat stubble, snowpack runoff is faster and greater with increased stubble height. Conceivably, vegetative cover can be manipulated as a management practice for soil water conservation and for soil temperature regulation.

SOIL MULCH

Any kind of mulch on the soil surface influences soil temperature. Many reports have been written on the use of plastic film of different colors, white and black gravel mulches, bituminous materials, felt, aluminum spray, roofing paper, aluminum foil, and vegetative mulches to alter the soil temperature. In general, dark materials and clear plastic cause the highest increase in soil temperature, resulting in faster seedling emergence and early growth and often shorter maturity time. However, care must be exercised so that plant growth is not too rapid or succulent because such conditions may increase disease incidence. Mulches of straw, corn stover, or other crop residues usually will decrease soil temperature. This temperature decrease may be more desirable in regions where high soil temperatures are a problem, compared to cooler regions where the additional cooling can cause problems, particularly with early plant growth.

Mulch may alter the amount of light energy reflected and the amount of net radiation. Apparently light-colored straw may reflect considerably more light than a bare, dark soil, and net radiation may be lower in the spring and early summer but higher later in the summer for straw-covered soil as compared with bare soil.

Mulches also affect soil water storage and subsequent plant growth and it is known that water content affects thermal conductivity, thermal diffusivity, and heat storage. Type of tillage can have a large effect on the amount and kind of mulch left on the soil surface.

Because soil water content can influence soil temperature, some success has been achieved in altering the soil temperature by irrigation. Changes in soil water affect plant growth through the change in soil water availability to the plant and through subsequent effects on the plant.

CROPPING INFLUENCES

All plants do not respond the same to a given soil temperature regime, and cardinal points of crop development differ from one phenological stage to another, indicating that crops respond differently to the environment during different developmental stages. For example, "optimum" soil temperature for corn seedlings is about 86°F, and for barley seedlings about 65°F. As the plants become older, the "optimum" is about 76°F for corn and about 59°F for barley. In addition, the "optimum" range is increased by proper plant nutrition.

Soil temperature significantly influences the availability and uptake of several plant nutrients, particularly P and N. This effect is coupled, of course, with soil water content and uptake. Soil temperature can affect initiation of tillers and adventitious roots of winter wheat. Plant transpiration is affected by soil temperature. Soil water stress and soil temperature interact to affect stomatal closure. Low temperature may cause a chill-induced water stress in plants; warm night temperatures can be detrimental to plant growth. Many interactions that affect plant growth include temperature-light-water and temperature-aeration. Soil temperature affects soil microbiological factors that, in turn, affect plant growth.

Most of the temperature-growth factors are conceviably described by formulation. One model uses factors of latitude, longitude, elevation, and estimates (by regression formulae) of monthly, mean annual maximum, mean annual minimum, and mean air temperatures to predict frost-free season, normals of degree-days, and potential evapotranspiration. Correlations of April through July air temperatures and precipitation with yield change have been used to predict wheat production. A means of defining the effective rhizosphere temperature of a plant at specific growth stages is also needed.

In summary, soil temperature and the general plant microatmosphere obviously can be altered by tillage and other land husbandry practices. Such alterations in soil temperature may have little meaning unless subsequent effects on the biological system, and effects on plant growth in particular, are identified and expressed for practical application. In the latter sense, the root system of a plant is highly dependent on soil temperature in the way roots function to (a) take up nutrients for growth, (b) absorb water for growth and transpiration, (c) produce metabolites for growth, and (d) provide a sink for carbohydrates produced in the above-ground part of the plant. Generally, soil temperature is more important for vegetative growth, whereas air temperature has greater influence during certain reproductive growth. The reported literature usually does not define particular temperature effects as related to distinct growth stages.

Whether temperature has a direct or indirect effect on plant growth is a moot question, particularly because we are primarily interested in some yield function, and the plant acts as an integrator of many individual factors. Thus, the need for more research is evident. As additional research information is obtained, alternatives for field management to most efficiently produce our food and fiber requirements can be determined. Such alternatives should allow the farmer greater flexibility for the particular type of farming

program he desires to pursue and thus provide him an opportunity for a more stable income.

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ROOT GROWTH, FUNCTION, AND SOIL CHARACTERISTICS

H. M. Taylor[1/]

NATURE, SCOPE, AND SEVERITY

Many different tillage systems are used within the United States. These systems have been developed because soils, climates, crops, and heritages differ from region to region. Other reports at this meeting discuss the effects of various tillage systems on soil characteristics. This report covers effects on root growth and function of soil characteristics that differ because of tillage. The report will focus on aspects of root growth and function that are of greatest importance in the North Central Region of ARS.

Plant roots absorb all the water and nearly the total requirement for 16 nutrients used by the plant for growth. The root system also anchors the plant in place and maintains normally erect plants in that position. In addition, some roots provide storage for plant metabolites, and all young roots probably manufacture some growth regulators. The water uptake, nutrient uptake, and anchorage aspects of root function are emphasized in this report because these are most often the ones that respond to tillage.

Classically, the tillage problem has been approached by the researcher using some particular tillage tool or system and then measuring plant response in terms of crop yield. Our tillage research must center more directly on how the soil environment is changed by tillage; how root growth, function, and death are altered by the soil environment; and finally upon the effects of roots upon crop growth and yield. The research in each of these aspects should be concentrated in a few centers of excellence.

No unifying theories currently exist that will describe and explain the reactions of plant roots grown for a full season in field soils. This theory is needed to be able to describe the reactions of root systems to soil characteristics altered by tillage.

When plants are developing normally, the plant usually is well hydrated at sunrise (-1 to -4 bars plant pressure potential). Soon after sunrise on a clear day, the plant starts dehydrating (plant pressure potential becomes more negative) because evaporation from leaves exceeds water uptake by the root system. The plant pressure potential continues to decrease until 1 to 4 hours after solar noon. After that time, evaporation from the leaves decreases because radiation load decreases. After a short lag, water uptake by the root system also starts to decrease. The plant rehydrates because evaporation is less than root absorption. The plant fully hydrates (-1 to -4 bars plant pressure potential) sometime during the night. The minimum plant pressure potential (maximum dehydration) during the afternoon probably depends upon many factors, but these relationships have not been adequately defined.

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Several models have been developed that describe the loss of water from the plant leaves. Soil tillage will affect soil characteristics that in turn will affect inputs to these transpiration models, but that discussion is outside my assigned topic.

Several models also have been developed that describe the uptake by water by the root system. Most of these models examine the resistances and the water potential gradients along the path of flow from bulk soil to the ground surface or to the plant leaves. In these models, water uptake from a specific soil volume is proportional to the length of roots in that volume and to the drop in water potential from bulk soil to the root xylem, and water uptake is inversely proportional to the resistances along the flow path. Water extraction from all volumes of soil explored by the root system is then summed and equated to evaporation from leaves minus that removed from or restored to the plant (a small fraction of total evaporation).

Two plants of the same genotype growing under the same environment will have about the same total root length if they have the same total leaf area. This relationship should prove useful to persons who attempt to model flow of water through the entire pathway from bulk soil to the above-ground atmosphere. The fractional distribution of this system is drastically altered by soil characteristics and probably also depends upon distance from the photosynthate source.

A few functional relationships have been developed for predicting rooting density (cm roots/cm^3 soil) of seedling plants. Other functions have been proposed for more mature plants, but much work remains before we can predict the effects of changes in soil temperature, soil aeration, soil water, soil strength, and other such variables on distribution of rooting density within the profile. Root system investigations are time consuming and require considerable expenditures for equipment. Models of rooting density as a function of soil characteristics should be developed for a few of the major crops to aid in comparing effects of various tillage systems.

A common mistake in the literature is the assumption that rooting density always increases in a particular soil volume until plant death occurs. Research is now showing that root death rate is drastically affected by both the photosynthate supply to the roots and the water content of that soil volume. Studies should be expanded to quantify the dynamic nature of root systems and to determine the effects of other soil and plant parameters on root death in field situations.

Uptake of ions from a specific volume of soil also is affected by rooting density. Models have been developed that relate ion uptake to rooting density, to diffusive conductivity (a function of water content and probably of aggregation), to buffering capacity, to ion concentration in the soil solution, and to time. Differences in tillage systems can cause changes in several parameters associated with these factors. Much field research is needed before we can achieve models that satisfactorily predict ion uptake under field situations. These models are needed to increase fertilizer efficiency.

Different tillage systems can cause large differences in crop anchorage. If the surface 10 to 15 centimeters of soil is too loose or is too hard for

the nodal (adventitious) roots to penetrate, tall crops are subject to lodging. After a windstorm during the dry summer of 1975 at Castana, Iowa, plots containing conservation tilled corn showed much more lodging than nearby moldboard plowed plots. Observations indicated that many of the nodal roots did not anchor in the conservation tilled plots but did penetrate deeply in the moldboard plowed plots. Some corn rootworm damage occurred in both plots, but the additional surface hardness of the conservation tilled plots seemed to be the primary reason for the additional lodging. Much more information is needed about nodal root formation and function under field environments.

PAST AND PRESENT RESEARCH

Plant root research in the North Central Region has been concentrated at Ames, Iowa, Columbia, Mo., Mandan, N. Dak., and Morris and St. Paul, Minn. Substantial research on plant root development and function is continuing at each of these locations with the exception of Mandan, N. Dak.

RESEARCH NEEDS AND APPROACHES

Research Needs

With better techniques for evaluating soil structure-soil water relations, the number of tillage operations can be reduced and yet maintain or improve crop yields. Methods will be developed for describing water and heat flow during infiltration and evaporation in soils structured and layered by tillage. The predictability of obtaining particular soil structures must also be improved because tillage-induced soil structure varies with soil type, water content, density, and implement operation. Soil fragmentation as predicted by soil mechanics and soil properties will be utilized to improve the specification of soil structure resulting from tillage. The influence of soil structure on heat flow will be evaluated to improve the root temperature environment in the northern section of this region.

With better root development, crop yields and quality will be improved, and the economic value of the land will be enhanced. Root development and water relations will be determined as affected by tillage to break up the tillage pan. Soil strength, tillage, soil texture, and their interactions will be studied to determine factors necessary to arrest or delay tillage pan development. Where these soils are irrigated, emphasis will be placed on use of tillage systems to handle large quantities of plant residue with the possibility that their placement may be used to aid in amelioration of tillage pans.

On clay soils, studies will be made to determine the influence of deep tillage on soil aeration, root development, soil water relations, and crop production. Depth of soil profile mixing also will be evaluated in these studies. The incidence of plant root diseases will be studied in relation to the factors of soil aeration, soil water, and root development. Management of these restricting soil layers will also be studied in relation to crops that have different rooting requirements. (This applies to the coarser-textured soils also.)

Research Approaches

Mechanics of Soil Deformation by Roots

Three types of root extension may be delineated: tap root and tuber enlargement, movement of root with root cap through soil, and root hair enlargement.

Are the important soil mechanical properties different for different kinds of root extension and soil deformation?

Can these soil deformations be simulated with simple geometrically shaped devices?

Can the mechanical aspects of soil deformation be utilized to predict root extension?

Can the mechanical aspects of soil, especially layered compaction, be used to predict site of tuber and tap root development and the resistance to enlargement? Does the site of development affect mechanical harvestability and quality of root crops?

Can the mechanical relations of emerging seedling and of soil be utilized to develop a basis for seedbed design to alleviate poor emergence?

Plant Shoot and Root Environment Requirements

Can improvement be made of the methods for describing root proliferation and morphology? With such improved methods, can such morphological factors be described as depth of wheat crown formation and number of tillers and depth of adventitious bud formation in corn and wheat?

Can we adequately describe all the parameters needed to use simulation techniques to describe total root growth response to interacting factors such as soil temperature, nutrient supply, water supply, mechanical resistance of soil to deformation, and aeration? How do these factors together affect root morphology as described in question 1? Do plant genotypes vary in terms of these requirements?

How does a root respond to sizable volumes of heterogeneity such as soil layering and extensively structured soils with distinct natural cleavage planes?

How do row spacings and plant populations affect root morphology?

How does planting depth affect root morphology and proliferation?

Is the shoot-to-root weight ratio related to root environment? What shoot response may be expected from alteration of root proliferation and morphology? Can chemical analysis of the shoot be used to identify existence of adverse root environment? Conversely, can plant shoots be treated with hormones or other similar materials to alleviate the effect of adverse root temperatures?

Can an optimum root volume be delineated such that separate row and interrow surface tillage treatments may be used to provide optimum root growth in the row and water conservation in the interrow? To what extent does this specification depend on row spacing?

Root Functions as Affected by Tillage

How does the distribution of plant roots within the profile affect water uptake?

How does the distribution and morphology of plant roots affect ion uptake from the soil?

Will root-feeding insects and root diseases be more prevalent under some tillage systems than under others?

How important are the changes in characteristics of soil volumes that are located deep within the profile but where the altered characteristics are caused by surface tillage systems?

How do we predict the effects of deep (less than 2 feet) profile disturbances on effectiveness of the root system in supplying water and nutrients?

CONSEQUENCES OF VISUALIZED TECHNOLOGY

Increased crop production by providing optimum soil conditions.

Improved quality of root crops.

Increased crop yield.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY

Interregional cooperation is needed to effect tillage systems on root growth. Submodels are needed to describe the effects of (a) tillage tools on soil characteristics, (b) soil characteristics on root growth and function, and (c) root functions on top growth and yield. Root research is so timeconsuiming that only through interregional cooperation can the necessary resources be marshaled.

NUTRIENT LOSS RESEARCH

R. E. Burwell[1/]

NATURE OF THE PROBLEM

In the mid-1960's when environmental quality and water pollution became a worldwide concern, agricultural fertilizers were frequently cited as a major factor contributing to the pollution of surface and groundwater. However, at that time, little factual information was available for assessing the cause and severity of the problem. Therefore, research was started in the North Central Region to determine the effects of various fertilizer management and other cultural practices on the overland and deep percolation movement of nitrogen and phosphorus. Research attention was directed toward these nutrients because they are commonly supplied by commercial fertilizers to meet the needs of agronomic plants and have been cited as contributing to profuse growth of algae and aquatic plants in lakes and ponds. In addition, the nitrate form of nitrogen occurring in drinking water at concentrations in excess of 10 ppm can cause an abnormal blood condition in infants known as methemoglobin.

Nutrient movement research during the past decade has reemphasized the need to control erosion from agricultural land because sediment has been a major transport agent of N and P. Research has also shown that the movement of soluble N is closely related to hydraulic characteristics of soils. Amounts of soluble N lost in surface runoff and concentration levels have been low for moderately permeable soils but higher than desired for slowly permeable soils, such as the claypans. Soil profile studies have shown little movement of NO_3-N below the rooting depth for moderately permeable and slowly permeable soils when annual fertilization is at rates recommended for efficient crop production. When nitrogen fertilizer application exceeds the recommended rate, considerable movement of nitrate may occur below the rooting depth.

PAST AND PRESENT RESEARCH

Much of the nutrient movement research has been conducted on standard runoff-erosion plots used to evaluate the effects of cropping, fertilization, and tillage and residue management on runoff and erosion under natural rainfall conditions. Studies conducted at Morris, Minn., on a moderately permeable soil showed that cropping practices that provided good soil cover during the critical erosion period greatly reduced soil erosion and associated N and P losses (Timmons and others, 1968; Burwell and others, 1975). The study also showed that average annual losses of soluble N and P were low (less than 2.5 lbs/A/yr) and that concentration levels of NO_3-N were well below 10 ppm. Similar studies conducted on a slowly permeable claypan soil near Columbia, Mo., showed that soil erosion and associated N and P losses were greatly

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reduced by no-till planting of corn where surface residues were retained on the soil surface (Smith and others, 1974; Whitaker and others, 1976; Mikulcik and others, 1976). The study also showed that runoff, soluble P concentrations and losses were greater from no-till planting than from conventional tillage. Although runoff was greater from no-till than conventional tillage, soluble N losses were about the same for these two practices because nitrate-N concentrations were lower for no-till planting than for conventionally planted corn. Nitrate-N concentration frequently exceeded 10 ppm for both tillage practices when runoff occurred early in the crop season after fertilizer had been incorporated into the soil. The study showed that rate, time, and placement of N fertilizer application are important factors affecting runoff losses of soluble N from claypan soils and that fertilizer use efficiency can be increased by improved management of fertilizer application (Whitaker and others, 1976).

Small plot studies have been conducted in Indiana using simulated rainfall techniques. These studies evaluated the effects of fertilizer application practices and tillage methods on runoff losses of N and P. Moe and others (1967) reported nitrogen losses up to 15 percent of that applied when ammonium nitrate was applied on sod and fallow plots and runoff occurred shortly after application. Moe and others (1968) reported that under applied rainfall conditions, total nitrogen losses ranged from 2.4 to 12.7 percent of the applied nitrogen and that ammonium N loss in runoff was less for urea treated plots than for ammonium-nitrate treated plots. Nelson and Romkens (1968) reported that phosphate concentrations in runoff water appeared to be related to rate of phosphorus application and that amounts of soluble P removed in 10 inches of runoff water were 1.0 and 1.26 percent of that applied at rates of 100 and 50 pounds per acre, respectively. Romkens and others (1973) reported small losses of soluble N and P in runoff for conventional tillage, but losses of sediment-associated nutrients for this treatment were greater than for other tillage treatments. A simulated rainfall study at Morris, Minn., showed the need to incorporate fertilizer into the soil to minimize runoff losses of N and P (Timmons and others, 1973).

Watershed studies were started on deep loess soil near Treynor, Iowa, in 1969 to characterize the movement of N and P by crop use, surface runoff, deep percolation and subsurface discharge as affected by recommended and excessive fertilizer rates and by contouring and terracing conservation practices. These studies have shown:

(1) Terraces were highly effective in controlling erosion and associated N and P losses, but contouring alone was not sufficient (Burwell and others, 1974; Schuman and others, 1973a; Burwell and others, 1976);

(2) Soluble N and P losses in runoff and concentration levels were low even when fertilizer was applied at 2.5 times the recommended rate (Schuman and others, 1973b; Burwell and others, 1975; Burwell and others, 1976);

(3) Nitrogen originating in rainfall that ran off was equivalent to two-thirds of the soluble N measured in runoff from a watershed fertilized at a normal rate (Schuman and Burwell, 1974);

(4) Little NO_3-N moved below the rooting depth for the watershed fertilized at the recommended rate, but considerable movement occurred when fertilizer was applied at 2.5 times this rate (Schuman and others, 1975; Saxton and others, 1976);

(5) Soluble N in subsurface flow from a watershed fertilized at a normal rate represented a large portion of the annual soluble N discharged to streamflow during a five-year study period (Burwell and others, 1976)--however, concentrations of NO_3-N were below 10 ppm for 57 of the 60 months sampled; and

(6) Nitrogen used by corn fertilized at the recommended rate was about equivalent to that applied annually which reduced the chances of fertilizer N moving into water supplies by runoff and deep percolation (Burwell and others, 1976).

Nutrient losses in surface runoff from forested watersheds have been determined in Ohio (Taylor and others, 1971) and in Minnesota (Timmons and others, 1976). A field plot study was started in west-central Minnesota in 1969 by D. R. Timmons (results not published) to determine runoff losses of N and P from native prairie grass for natural precipitation conditions. This information from nonagricultural land resource areas will provide a basis for evaluating man's influence on surface water quality.

RESEARCH NEEDS AND APPROACHES

Experimental objectives, procedures, and results have varied widely among the many nutrient movement studies conducted within the North Central Region. The lack of common regional objectives, procedures, and management variables has not permitted a systematic approach to the nutrient loss and water pollution problems. Some of the independent research was justified because it provided answers to localized specific questions for a prescribed set of soil-climatic-management conditions. Increased coordination among research locations is needed to achieve basic objectives in regional nutrient movement research.

Scientists concerned with the movement of chemicals from agricultural land need to adopt a new philosophy in their research. Simply, improve use efficiency of agricultural chemicals. We know that--as soil and water move, so move N and P. We know that strip-cropping, terraces, and conservation tillage practices can help control soil movement from agricultural land. Retaining crop residues on the soil surface by conservation tillage practices can be highly effective in controlling erosion and associated N and P losses. We also know that some conservation practices alter the pathways by which water moves from watersheds, although these practices may not materially alter total water discharge. Tillage-infiltration research in Minnesota has shown that tillage, or lack of it, can have a tremendous effect on infiltration and runoff. Runoff-erosion studies on the slowly permeable claypan soil in Missouri have shown an infiltration advantage for tillage. Soluble N concentrations have been greater from conventional tillage than from no-till. Soluble P concentrations and losses were greater from no-till than conventional

tillage because of greater runoff and reduced sediment loads and subsequent adsorption of P by sediment.

More research is needed to characterize the effects of tillage-induced physical parameters on soil chemistry and biology as they influence nitrogen mineralization and denitrification transformations. Tillage and surface residues have been shown to influence soil thermal and moisture properties, but information is limited on their effect on chemical and biological processes. Little is known as to the effects of tillage on soil insects and diseases that attack crop plants. Conservation tillage frequently accelerates the weed problem, which requires the use of larger amounts of herbicides. This may increase water pollution hazards and crop production costs. New information is needed as to what extent tillage can be utilized to overcome these crop production problems.

Greater effort needs to be expended toward an economic evaluation of conservation practices. To accomplish this, a total systems approach is needed which requires team effort among many disciplines. We need to know if a specified practice is a paying or costing proposition. Inquiries are frequently made as to the value of a ton of topsoil and to what extent conservation practices are economically practical. For example, a market is being established for corn stalk residues that are being used for synthetic rubber production. Removal of corn stalks from crop land will create additional erosion problems if this market becomes substantial. Management alternatives to corn residues must be found if that happens.

In addition, soybeans provide little residue soil cover for erosion control. Research is needed to determine nutrient movement from soybean cropping systems because soybean acreage is substantial in the North Central Region. Providing winter cover and multicropping practices appear to be very attractive alternatives. However, cultural management practices, including tillage, will need to be developed for a successful change from monocropping to multicropping systems.

Research is needed to establish relationships of N and P concentrations in field soils to the concentrations of these nutrients in eroded soil (sediment). This information used in conjunction with the Universal Soil Loss Equation would provide a basis for predicting sediment-associated nutrient losses from agricultural land.

EXPECTED BENEFITS

A potential benefit of nutrient loss research will be improved use efficiency of fertilizer. This will reduce production costs and increase crop production or both per unit of input. The research has reemphasized the need to prevent excessive erosion from cropland. When erosion control is accomplished, two benefits will be the retention of soil for future crop production and cleaner surface water supplies. The improvement of present conservation practices and the development of new practices will contribute toward achieving this goal.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

A basic requirement for developing a chemical transport model is intensive coordination of specialists in many scientific fields including soil chemistry, hydrology, erosion, crops, soil physics, tillage, weed control, disease control, insect control, and machinery design. These people would draw on local, area, regional, and national knowledge to develop a basic model and submodels required to predict nutrient losses for various crop-producing systems. Initial efforts would be directed toward developing interdisciplinary understanding and remedial action. Data assembly and study would provide a basis for establishing future research needed to improve the models.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

Leadership among, as well as within, scientific disciplines needs to be established. Provisions are needed for data gathering and analyses beyond the local level. Some redirection of local, area, and regional research would be needed as established by interdisciplinary leadership. Local scientists would look toward this leadership in directing their research activities to generate data needed for regional and national predictive models. The local scientist would coordinate his research with state experiment stations and state action agencies.

Personnel and physical facilities required to obtain additional data needed would be determined after a thorough study of existing data.

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SOIL CRUSTING

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NATURE AND SCOPE

Wetting and subsequent drying of soil surfaces cause physical changes in the upper few millimeters of the soil that make it denser, decrease the size and amount of large pores, and reduce the surface permeability to water, air, and plants. This compacted surface layer, which can be visually distinguished from relatively undisturbed soil below, is commonly called a soil crust.

On agricultural soils, crusts cause two major problems: seedling emergence is hindered and runoff is increased. In some situations, the reduced permeability of crusts to water vapor, O_2, and CO_2 also reduces crop yield.

Cotton and sugar beets are the major field crops hurt most by crust-induced reduction and failure of seedling emergence. In some regions, about 20 percent of the sugarbeet acreage is replanted, frequently to a less-productive, shorter-season crop. The USDA-ARS (USDA, 1975) estimates that because of crusting, 500,000 acres of sugarbeets and 3,000,000 acres of cotton are replanted annually. Crop yield (production) is no doubt reduced on many more acres on which replanting cannot be justified. Crusting also causes widespread emergence problems in the lettuce, tomato, and other high-value vegetable crop producing areas of the country, especially in the irrigated valleys of the southwest (Cary and Evans, 1974).

From the runoff-producing standpoint, crusting is a more widespread, persistent problem. The crusts that reduce emergence for a short time after planting continue to limit infiltration, increasing runoff and its associated erosion and chemical transport long after crop emergence. The crusting problem is most severe on tilled soils that are not protected by vegetative cover. These are high sediment delivery areas with potential for erosion of 100 tons per acre per year if proper management and erosion control practices are not used (Walker and Wadleigh, 1968).

Increased herbicide usage for weed control in cropland influences soil crusting from two opposing standpoints. Herbicides used in a minimum- or no-tillage system allow dead vegetation, frequently a killed sod, to protect the interrow area (Larson, 1964) from raindrop impact, reducing crusting and increasing infiltration. However, replacing one or more mechanical cultivations with herbicides for weed control in conventionally tilled row crop systems eliminates the crust-breaking operations which could potentially restore high infiltration rates.

Replanting costs caused by crusting may be as high as $10 million annually (USDA, 1975). Tomato growers in Ohio estimate over $100 per acre in annual production costs could be saved if they could seed directly, rather than

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transplant. When the costs of reduced yields, accelerated runoff, erosion, chemical transport, and energy consumption are included, cropland crusts become unbearably expensive.

PAST AND PRESENT RESEARCH

Crust Formation

Many aspects of soil crusting have been researched during the last two decades. Early work defined the falling water drop as a crust maker and related drop size to terminal velocity (Ekern, 1950), intensity (Laws and Parsons, 1953), and infiltration and erosion rates (Laws, 1940). However, wetting and subsequent drying without high impact energies can also produce crusting (DeBoodt, 1972).

Crusting has also been related to soil physical characteristics. Texture, mineralogy, soil chemistry, and organic matter content effects are thoroughly discussed and cited in Cary and Evans (1974). Manageable soil features such as aggregate size, strength, and stability (Moldenhauer and Long, 1970; Moldenhauer and Kemper, 1969) and surface roughness have also been evaluated in their effects on crusting. The strength of crusts has been related to rainfall intensity, soil characteristics, and management practices (Epstein, 1970).

In laboratory, plot, and watershed research a densely vegetated surface cover prevents soil crusting. The effects of vegetation on runoff and infiltration are thoroughly described in research reviewed by Parr and Bertrand (1960) and Cary and Evans (1974).

Seedling Emergence

The upward force exerted by seedlings relative to the strength of the crust determines emergence. Seedling emergence force has been measured for cotton (Drew and others, 1971) and related to soil temperature. Similar work has indicated the emergence force of several legumes (Jensen and others, 1972; Williams, 1956), corn (Prihar and Aggarwal, 1975), lima beans, corn, cucumber, cotton, radishes and tall wheatgrass (Gifford and Thran, 1969). These and similar studies (Holder and Brown, 1974; Hatfield and Egli, 1974) have shown that seed size, weight, and orientation; soil and crust water content; soil temperature; cumulative degree days; and soil compaction around and below the seed (Futral and Verma, 1974) all affect emergence through crusts. Wetting and drying rates and soil aggregate size have also been related to seedling emergence (Johnson and Henry, 1974).

Emergence can be improved by soil conditioners. Under some field conditions, row-banded Krilium increased sugarbeet emergence 100 percent (Smucker and Leep, 1975). Phosphoric acid (Anderson, 1974), butadiene styrene, polyvinyl proprionate (Smucker and Leep, 1975), asphalt, waxed paper, plastic, polyvinyl alcohol, vermiculite (Short and Kretchman, 1974), perlite, gypsum, and manure (Holder and Brown, 1974) have been studied as potential aids to seedling emergence.

A moist crust over the seedling row is more easily penetrated than a dry crust (Drew and others, 1971; Arndt, 1965). Van Doren and Henry (1973) planted sugarbeets in single-seed compressed wafers of vermiculite to get better stands. Cracks in the crust which improve emergence can be controlled under some conditions (Johnson, 1962; Hemwell and Scott, 1962), and emergence through holes punched through the crust at planting (Heinemann and others, 1973) can result in better crop stands.

Various planting, management, and bed shaping techniques which promote seedling emergence have been summarized in Chapter 1 of Cary and Evans (1974). Other good summaries of research on soil crust strength and seedling emergence are available (Drew and others, 1971; Baver and others, 1972).

Runoff Generation

Many years of observation and watershed runoff research show that crusted soil surfaces caused more runoff and less infiltration than do surfaces protected by a vegetated cover (Harrold, 1951). An unpublished analysis of more than 200 runoff-producing storms falling over a 24-year period on eight ARS watersheds at Coshocton, Ohio, shows that clean tilled surfaces have more runoff when the soil is crusted at the beginning of an event than when it is not crusted. Duley (1939) showed under controlled conditions that the development of a surface crust greatly reduced infiltration.

Crusts decrease the initial and equilibrium infiltration rates and the time required for establishing the equilibrium rate (Hillel, 1959). Laboratory measurements of the effect of simulated rainfall amounts (Edwards and Larson, 1969) and drop energy (Moldenhauer and Long, 1970) on infiltration through crusts have been made. Techniques have been presented for measuring the hydraulic conductivity of crusts in the laboratory (Edwards and Larson, 1969) and in the field (Bouma and others, 1971).

Laboratory-determined values of water flow characteristics of soil crusts can be used to model infiltration of water under crusted steady state (Hillel and Gardner, 1969) and transient conditions (Hillel and Gardner, 1970). Further discussion and reference citations concerning the effect of crusts on infiltration and runoff are presented in Cary and Evans (1974) and Falaya and Bouma (1975).

RESEARCH NEEDS AND APPROACHES

Much has been learned in the past 30 years of the mechanisms of crust formation, crust prevention, and the effects of crusting upon infiltration and runoff. What remains, for the most part, is to compile available results into a usable form. High priority should be placed on developing a functional system for determining how individual crust problems should be avoided or solved. A model should be developed responsive to weather, soils, crop history, and other inputs that can define the expected effects of different anticrusting managements. Enough background research has been done to enable a rational choice among potential solutions to best do the job in different situations. The model would also indicate areas where further research may be needed.

Crusting research objectives need to be coordinated with investigations into other tillage-related problems. For example, investigations of surface crusting on a fragipan soil should be planned with an awareness of parallel soil compaction research that may recommend deep mixing to improve the deep rooting zone. Similarly, anticrusting research on soils that have traditionally been clean tilled should not be concentrated if new drainage concepts are soon to enable the application on these soils of no-tillage systems with surface protecting mulches. The best way to manage surface crusting may well depend on the eventual solutions of drainage, salt, pest, soil temperature, or other problems.

The effect of replacing mechanical cultivation for weed control with chemical herbicides needs to be thoroughly evaluated. Again, much of the basic work has been done, but past records and data need to be examined to define emergence, runoff, erosion, and chemical transport when a crust is allowed to persist undisturbed throughout the growing season on soils that were formerly cultivated several times in the spring. One approach may be through relating expected weather inputs to runoff data and infiltration rates or both through crusts.

New potential anticrustants, for example, super slurper (Weaver and others, 1974), are continually being developed. Coordinated examination of effectiveness of these new chemicals should be made over a wide range of soils and locations. The primary objective should be the development of a good anticrustant. Rather than trying to adapt an existing product into anticrusting application, we need to use the soil physical and chemical research backlog to define the needed characteristics of an anticrustant and develop a product to do the job.

In a new technology assessment of the future for minimum tillage, USDA researchers predict that by the year 2010 about half of our crop production will be by a no-tillage system and most of the remaining crop land will be farmed with other minimum tillage systems (Lessiter, 1975). Because a tillage system that leaves a mulch cover on the surface is favored from a crusting standpoint, extending similar practices into areas where they are presently not accepted needs to be developed. The major thrust of research should be in adapting present systems to suit a wider range of soil, climate, crop, and pest problems.

EXPECTED RESEARCH BENEFITS

Removing the adverse effect of crusting will improve stands and increase yield and production of several field and vegetable crops.

Getting a satisfactory stand the first time will eliminate the energy requirements of replanting.

Reducing crusting will lessen runoff, erosion, downstream pollution, and requirement for treatment of water for downstream uses.

Reducing runoff and erosion will increase use of fertilizers and pesticides at the site of application.

Reducing crusting will mean more infiltration and more available soil water to increase yield and production on drouthy soils.

POTENTIAL FOR EXTRAPOLATION THROUGH MODELING

Seedling emergence as a function of different anticrusting treatments could be modeled. With predicted weather inputs based on storm energy records, the degree of anticrusting control required could be determined for any soil-crop-location-year combination.

We have enough background research to add to any existing watershed runoff model the effect of crust versus no crust antecedent conditions.

When deep tillage and mixing is required to alleviate a drainage, root restriction, or chemical problem, the predicted crustability of the resulting surface would help determine the optimum mixing depth and pattern.

RESOURCES REQUIRED

Much of the basic research has been done. The next step is to evaluate the use of available information in meeting current crusting and other tillage research objectives.

Public policy and regulation will have an increasing effect on the land management options available to the farmer. Therefore, crusting research should be coordinated with tillage and other land management goals that consider future policy, regulation, and long-range forecasts of land use and crop production systems. Where technology and land use policy indicate that clean tillage on susceptible soils will continue for the significant future, solutions to crust problems can be formulated from a model based on existing research results. If existing solutions are not apparent, research directed toward solving specific problems should be planned within the framework of the general tillage model.

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SOIL COMPACTION

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NATURE OF THE PROBLEM

The purpose of tillage is to create soil conditions necessary for crop production while protecting soil and water resources and conserving energy. Inherent in this broad purpose are many distinct problems involving many interrelated disciplines. One such problem is that of soil compaction. Soil compaction is caused by a combination of natural forces, which generally act internally, and by man-made forces related to the consequences of agricultural technology. The latter forces are mainly those related to vehicular wheel traffic and tillage implements and likely have a much greater compactive consequence than such natural forces as rain drop impact, soil swelling and shrinking, and tuber and root enlargement. Compaction, whatever the origin, rearranges the soil particles so the total pore space is reduced, the average pore diameter is reduced, and increases the cohesiveness of the soil mass. Consequently, the movement and storage of water, heat, and gases are altered, as well as the ability of the soil to resist such applied forces as tractor wheel, plant root, tillage tool, or water and wind. Thus, root growth and plant yield can be affected, traction and draft requirements are affected, and erosion by water and wind can be affected.

The scope of man-induced soil compaction includes practically every acre of the more than 300 million acres annually cropped in the United States since most crops involve some form of vehicular traffic at some stage of their development. Other sources of soil compaction may not be as widespread. Compacted soil at the bottom of the tilled layer will occur only under certain combinations of soil type and tillage practices. Genetically developed compact layers such as claypans or fragipans are also somewhat localized geographically. Thus, in terms of scope, the agricultural significance of vehicular wheel traffic must rank as the main research need in the area of soil compaction. This is accentuated by the ever-increasing weight of tractors, tillage implements, and harvesting equipment. At the same time, this trend towards larger machinery size offers new potentials for managing wheel traffic and soil environment to increase crop production.

In terms of crop response, over 50 million acres of corn and soybeans in the Midwest may be affected by either excessive wheel-induced compaction or mismanagement of wheel traffic. More than 15 million acres of cotton, sorghum, and soybeans in the Southeast and Southern Plains can be expected to have reduced yield because of rooting restrictions related to wheel-induced compaction. Over 3 million acres of sugarbeets, vegetables, and cotton throughout the nation frequently need to be replanted because compacted soil prevented seedling emergence. The quality of root crops can be seriously affected by

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soil compaction on over 1.5 million acres[2/]. But the severity of the problem must be evaluated in terms of total agricultural significance. Thus, considering soil erosion and fuel economy, in addition to both favorable and unfavorable plant responses, even modest levels of soil compaction may have significant agricultural impact.

PAST AND PRESENT RESEARCH

A major thrust in past and present research has been concerned with fundamental relations between soil and tillage tool, and soil and traction devices (tires, wheel, tracks). In spite of having gained a tremendous amount of knowledge about the dynamics of soil deformation, a generalized equation to mathematically describe the compaction behavior of soil in response to an applied force is lacking. Soil texture, moisture content, initial bulk density, organic matter content, rate of loading, boundary conditions--all have an effect such that compaction, as applied to a field situation, appears not to be a unique function of applied stress but may also be related to shearing strain.

Unlike soil dynamics principles which benefited from a concentration of facilities like the National Tillage Laboratory at Auburn, Ala., soil compaction research as an agronomic factor has been limited. The main thrust to date has been with cotton and soybeans in the southern states. The soil and climate situation there results in rather obvious wheel-induced mechanical impedance problems which restrict downward water movement and deep root growth, resulting in yield decreases. Alfalfa root growth restrictions due to wheel traffic have also been noted in California. Most field research outside of the southern states was conducted 20 to 30 years ago. Field equipment used then did not seem to produce compaction to the extent of affecting yields, nor was any long-lasting soil compaction noted in the northern states. This led to a general lack of research interest and also contributed towards the attitude that wheel traffic-induced compaction was not a problem north of the hard-freeze line. However, recent field studies in Minnesota suggest that with modern-day equipment, wheel traffic may indeed be compacting the soil in ways which may have long-lasting agricultural significance including yield increases under certain climatic conditions. Several people have published data showing the effects of mechanical resistance on reducing root elongation under rhizotron and laboratory conditions, but these results are generally difficult to extrapolate to field conditions.

RESEARCH NEEDS AND APPROACHES

Several aspects of soil environment are influenced by the compactness of the soil. This includes air, water, heat, and soil strength. In turn, these factors affect plant growth and soil biological activity. The greatest research need is a coordinated integrated effort between soil, engineering,

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[2/] Agricultural Statistics 1974 and the National Research Program on Tillage Practices for Improving Soil Properties and Crop Growth, U.S. Department of Agriculture.

and plant sciences based on the realization that we need to know how a plant will respond to a given set of soil-climate environments before we can recommend engineering or management changes with respect to wheel traffic compaction. Since all wheel traffic can't be practically eliminated, it must be controlled for the benefit of not just the plant, but also for the purpose of minimizing loss of natural resources and for conserving energy. The magnitude, depth, and persistence of soil compaction will depend on a variety of soil-machine interactions; the plant response to this compaction will depend on a variety of plant-soil-climate interactions. Neither of these two sets of interactions can be adequately and completely researched under laboratory conditions. This does not preclude the need for a facility like the National Tillage Laboratory. Rather it complements their program. Also, plant response to a given set of conditions must be measured ultimately under field conditions. Again, this complements rather than precludes basic plant growth research in a greenhouse, growth chamber, or rhizotron. Also field studies include the climate variable which cannot be duplicated. Thus, the research approach must be coordinated, involving a range of physiographic areas cutting across several disciplines with the following objectives:

1. Laboratory tests need to be developed for predicting potential degrees of compaction to be expected from a given farming practice for a given soil condition. Basic theory developed at the National Tillage Laboratory and elsewhere provides good background for doing this. Measurements made in St. Paul suggest some practical ways of achieving this goal.

2. Assuming the degree of compactness can be predicted, published data exist whereby changes in soil water, heat, air, and strength can be calculated to a certain extent. Some field measurements may have to be made to fill in gaps and check calculated values.

3. Plant response to compaction will depend on climate and plant species. Response in Minnesota is often opposite to that observed in the South. Objectives 1 and 2 above can be used to select a few sets of conditions for field testing since all possible combinations of soil-plant-climate can't be subjected to rigorous field testing. Several disciplines are needed to research the following plant and biological responses to soil compaction:

a. Soil temperatures in wheel tracks may be 2° to 3°C warmer or cooler depending on soil moisture conditions. This can be important in northern latitudes where soil temperatures at planting time are often below optimum germination temperature. Volumetric water content may easily be 10 percent higher in compacted soil. Under dry conditions this may be very beneficial. Lateral water movement can be altered by wheel traffic. This may affect uptake efficiency of banded fertilizer.

b. Soil compaction may decrease root elongation rate and rooting depth, but root branching may be increased. Compacted soil may restrict tuber and storage root development, thereby decreasing yield and quality of root crops. The physiological reasons for these responses must be known to make more efficient use of water and nutrients.

c. Soybean nodulation is affected by wheel traffic. What are the responsible biological processes? How do the plant and soil micro-organisms compete for limited photosynthate in compacted soil? How is total nitrogen fixation affected?

d. By altering the mechanical resistance, temperature, and water regimes in the soil, how is pest control affected, for example, weeds and corn rootworm?

4. Draft requirements and fuel consumption are often increased when tilling compacted soil. Traction is also increased, however. These will depend on soil types and moisture content, and need to be measured for present large equipment.

5. Compacted soil will have a lower infiltration rate, thus increasing the potential for water runoff. Compacted soil will have higher soil strength, making it more resistant to erosion by wind and water. Net benefits must be determined for various sets of soil-climate combinations.

Specialized equipment and facilities exist at various locations to measure some of the above factors. These should be shared when possible.

EXPECTED BENEFITS

Yield responses up to 35 percent have been measured for a variety of crops including corn, soybeans, wheat, potatoes, cotton, and alfalfa. These responses have occurred because of proper management of wheel traffic for a given set of soil conditions.

Because infiltration is less with compacted soil, the controlling of wheel traffic will lessen runoff and erosion. The proper management of mulches in combination with wheel traffic will also reduce erosion.

Energy efficiency in terms of fuel consumption and draft requirements can be increased 5 to 10 percent by controlling wheel traffic. Wheel slippage can be decreased, saving 10 to 15 percent tire wear.

The quality of root crops will be improved. Potatoes and other root vegetables will be better shaped, making them more appealing to consumers.

By increasing root density, plants will make more efficient use of fertilizer and water. Herbicides and insecticides will be more effective.

INTERREGIONAL EXTRAPOLATION

By developing laboratory techniques to predict soil compaction based on a few fundamental characteristics of the soil, and by establishing basic plant responses to given set sof soil-climate environments, the results from this new technology will have nationwide application. Results can be incorporated into a tillage guide, or the presently used wind and water erosion equations.

WATER EROSION

W. C. Moldenhauer[1/]

Many startling statements have been made over the years concerning soil erosion in the United States. An estimated 4 billion tons of sediment enter our surface waters annually (Williams, 1967) compared to a 3 billion ton estimate almost 30 years earlier (Bennett, 1939). Now, however, this lack of progress in controlling erosion may finally reverse. State governments, in response to pressure from the Environmental Protection Agency, are developing legislation to sharply curtail soil erosion.

Looking to the future with legal controls on soil erosion, we might well ask how well equipped we are to recommend practical control systems to farmers and contractors. In the 50 years since erosion research began, agriculture has changed dramatically. Have we been able to keep up and develop control measures to fit the needs of modern agriculture?

As more and more states adopt legislation, the pressure will continue to increase to furnish as many alternatives as possible to farmers and others over a wide variety of situations. If we are not ready, other agencies will fill the vacuum and with results that may be found much less than ideal.

PAST AND PRESENT RESEARCH

The first plots to measure soil and water losses were set up near Columbia, Mo., in 1917 by M. F. Miller and reported by Duley and Miller (1923). In about 1928, 10 cooperative Federal-State erosion research stations were started. Within the next 25 years, erosion plots were established at 32 additional locations. Precise measurements of precipitation, runoff, and soil loss at 42 stations in 23 states were continuous for 5 to 30 or more years (Wischmeier, 1972). Most of these plots have now been discontinued. A few could be reactivated, but many are no longer in existence. In recent years most of the research has been conducted using standardized simulated rains and a rain simulator patterned after the rainulator developed by Meyer and McCune (1958) or the type developed by Swanson (1965). Data have been gathered in Indiana, Minnesota, South Dakota, Nebraska, Iowa, Georgia, Illinois, Hawaii, and Puerto Rico, using siumlators based at Lafayette, Ind., Morris, Minn., Lincoln, Nebr., Watkinsville, Ga., and more recently Ames, Iowa, and Urbana, Ill. ARS research in water erosion is now going on at Morris, Minn., Lincoln, Nebr., Columbia, Mo., Ames and Treynor, Iowa, Lafayette, Ind., and Coshocton, Ohio. At most of these locations research is being done on erosion control aspects of surface residue tillage.

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RESEARCH NEEDS AND APPROACHES

Much effort has been spent over the past 50 years to measure soil and water losses from crops and cropping systems. A concentrated effort has been spent in the past 20 years to predict soil and water loss from cropping systems, which has been highly successful. The Universal Soil Loss Equation is in use over much of the United States and some foreign countries and modeling efforts are in full swing to measure loss of water, sediment, and agricultural chemicals from farmland. The effort in developing acceptable surface residue systems and some waterway work is to develop control systems for cropland erosion. Many of the practices in use today were developed by Soil Conservation Service (SCS) engineers with improvements from time to time to make the practices more acceptable to farmers. Research in developing systems to control field erosion is difficult because conventional research methods and attitudes do not apply. In spite of this, a serious effort must be made by ARS and SCS to combine talent to discover, adapt, or develop a range of alternative practices.

A flurry of this type of activity began in Iowa in 1964 or 1965 with the seeded backslope terraces. ARS and SCS teamed up on a research and development effort. Research results have been reported from Treynor (Burwell and others, 1974; Schuman and others, 1973) and Ames, Iowa (Hanway and Laflen, 1974; Laflen and others, 1972) and from Lincoln, Nebr. (Wittmus and Woodward, 1971; Wittmus and Peterman, 1971; Wittmus, 1973). Development efforts were reported by Jacobson (1967, 1968). Possibilities for virtually complete control of cropland erosion have been pointed out by Laflen and Moldenhauer (1971) and are being investigated by the Morris, Minn., group at Eagle Lake near Willmar. More of this kind of effort is needed.

Far and away the most acceptable measure for combined control of wind and water erosion is surface residue tillage. Reductions in soil loss from these tillage systems are well known and well documented. Unfortunately, the protection afforded by these systems is limited. On long or steep slopes, runoff discharge may float away or undercut mulch, causing excessive rates of soil erosion. Much research has been done on the effect of various tilled zone characteristics on crop response. But much research is needed on the tillage-mulch-soil type interaction to design a tilled zone for minimum runoff. This will cut discharge rates and thus increase the erosion control capabilities of the systems. Mannering and Meyer (1963) have shown that 2 tons of straw mulch spread on freshly moldboard-plowed soil reduced both soil loss and water runoff to essentially zero. Although this is not practical as a system, it does show what can be done with stirring of the tilled zone to achieve a high hydraulic conductivity and enough mulch to eliminate surface sealing. This should be possible with no-tillage on soils that have naturally high hydraulic conductivity. Soils that become dense and slowly permeable over time as they are cropped need stirring to maintain high infiltration. In all cases, mulch is needed to eliminate surface sealing as completely as possible.

EXPECTED BENEFITS

The most beneficial aspects of this research are in the area of pollution abatement by reducing sediment and sediment-borne pollutants entering surface

Much of the phosphorus removed from farm fields is absorbed by sediment (Burwell and others, 1974; Wadleigh, 1968). If erosion is eliminated, much of the removal of phosphorus is also eliminated. A number of pesticides, notably the chlorinated hydrocarbons and organo phosphates, are also greatly reduced from runoff water if sediment is eliminated (Holt and others, 1973). They point out any practice that increases soil organic matter will assist in holding most pesticides in place. They also point out, however, that appreciable amounts of dissolved chemicals may still be contributed to streams and impoundments by water runoff from agricultural land even though the sediment is eliminated. If tillage consists of chisel plowing as primary tillage and disk or field cultivator as secondary tillage, the energy saving is slight or nonexistent.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

If components of a tilled zone important in erosion control can be identified and quantified, a predictive model should be possible. These components might be hydraulic conductivity, surface mulch distribution, surface and tilled zone water storage, and propensity toward surface sealing. Factors such as bulk density and clod size distribution affect hydraulic conductivity and surface sealing and should contribute to predictability. In short, the tillage-mulch-soil type interaction should provide a basis for modeling and prediction of infiltration and erosion over a wide range of conditions. Enough data should now be available to make a first attempt at a model. Gaps in knowledge should become quickly apparent.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

Considerable research is planned or in progress in the North Central Region that would contribute to a modeling project. What is lacking is a modeler who will take the time and effort to develop a reasonable model. Then he or she could make sure the needed data are collected from tillage-erosion experiments throughout the North Central Region (or the entire United States). Collecting data for the modeling effort would probably not require great extra effort on the part of the individual researchers and would interfere very little with the original objectives of their research.

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TILLAGE RESEARCH NEEDED TO REDUCE WIND EROSION

E. L. Skidmore[1/]

NATURE OF WIND EROSION PROBLEM

Wind erosion is severe in many areas of the world and is the dominant problem on about 30 million hectares of land in the United States. On the average, about 2 million hectares are moderately to severely damaged each year. Extensive soil erosion in the Great Plains during the last half of the 19th century warned of impending disaster, and during the 1930's a prolonged dry spell culminated in soil destruction and disastrous dust storms on the Great Plains (Svobida, 1940; Malin, 1946a, b, c; Johnson, 1947).

Although generally believed to be important only in semiarid and arid areas, soil erosion by wind may occur wherever soil, vegetative, and climatic conditions are conducive. Such conditions exist wherever (1) the soil is loose, dry, and reasonably finely divided; (2) the soil surface is smooth and vegetative cover absent or sparse; (3) the field is large enough; and (4) the wind is strong enough to initiate soil movement (Food and Agriculture Organization of the United Nations, 1960).

Those conditions are met oftener in semiarid and arid areas where precipitation is inadequate or where the vagaries from season to season or year to year prevent maintenance of crops or residue cover on the land. The combination of conditions also occurs in subhumid and sometimes even humid areas. Vegetable crops are often damaged on sandy soils in areas of high rainfall.

Wind erosion physically removes the most fertile portion of the soil and, therefore, lowers productivity of the land (Daniel and Langham, 1936; Lyles, 1975).

Blowing soil fills ditches and fence rows, blocks highways, reduces seedling survival and growth, and lowers the marketability of vegetable crops.

Some soil from damaged land enters suspension and becomes part of the atmospheric dustload (Hagen and Woodruff, 1973). Dust associated with wind erosion obscures visibility, pollutes the air, causes automobile accidents, fouls machinery, and irritates homemakers.

PAST AND PRESENT RESEARCH

Numerous studies of wind erosion mechanics and control led to the development of a wind erosion equation (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965) and establishment of the following basic principles (Woodruff

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and others, 1972) to control wind erosion: (1) establish and maintain vegetative or nonvegetative land cover; (2) reduce field widths along prevailing wind direction; (3) produce stable clods or aggregates on the land surface; and (4) roughen the land. Three of those principles relate directly to tillage operations.

Since the value of residue for wind erosion control was recognized, various studies (Woodruff and others, 1965a, b; Fenster and others, 1965; Woodruff and others, 1966; Woodruff and Chepil, 1958; Fenster and McCalla, 1970; Anderson, 1965; Anderson, 1961) have evaluated performance of tillage implements in a stubble-mulch system.

Two types of tillage machines were used in stubble mulching: (a) those that stir and mix the soil, and (b) those that cut beneath the surface without stirring or turning the tilled layer. With either type, the quantity of residue conserved is a function of quantity, height, or length, and previous positioning of pretillage residue. Subsurface sweeps conserve more residue than do such mixing type implements as one-way disks.

Experimental results show that stubble mulching and reduced tillage leave more residue and leave it more erect than conventional tillage does; consequently, providing more effective wind erosion control (Anderson, 1961; Fenster, 1960; Unger and others, 1971; Woodruff and others, 1965a; Schmidt and Triplett, 1967; Schmidt and Kroetz, 1969; Moldenhauer and Duncan, 1969; Duncan and Moldenhauer, 1968).

Past research on tillage to control wind erosion was centered at Manhattan, Kans., with scientists at other Great Plains locations participating: in Kansas (Colby, St. John, Garden City, Hays, Tribune), Nebraska (Alliance, Lincoln), Texas (Big Spring, Bushland), and Colorado (Akron). Corn Belt locations of Ames, Iowa, and Wooster, Ohio, have contributed, as has research at Swift Current, Saskatchewan. Present ARS locations with support for wind erosion research are Manhattan, Kans., Big Spring, Tex., and Sidney, Mont., with 5.2, 0.8, and 0.4 SY's respectively. Since tillage, particularly residue management, plays such an important role in wind erosion control practices, a portion of the support likely is devoted to tillage aspects.

RESEARCH NEEDS AND APPROACHES

Tillage research needs applied to those principles for controlling wind erosion may include the following objectives: (1) to develop tillage that will reconstruct the fine soil particles and aggregates into stable aggregates larger than 1 mm but small enough for a good seedbed; (2) to develop tillage that will leave a blanket of stable clods on the surface; (3) to develop tillage and residue management to minimze overwinter breakdown of soil aggregates on soils susceptible to wind erosion; (4) to optimize tillage for producing soil roughness; (5) to develop tillage that will conserve and manage residue for erosion control and maximum crop yields; (6) to evaluate interaction between tillage and cropping history on soil physical properties, particularly those that relate to wind erodibility. Research approaches listed in ARS National Research Program 20800, Technical Objective 2 (Wind Erosion . . .) that include tillage aspects are:

-- Improve wind erosion control from crop residues after tillage: Conduct no-till, minimum, and stubble mulching research to determine optimum orientation of residues; develop improved herbicide-tillage techniques, improve the role of sequence and frequency of operations, and improve drilling and planting procedures.

-- Improve wind erosion control from tillage manipulation of soil structure: Conduct research to evaluate clod production characteristics of various tillage machines, determine optimum critical friction velocity ratios for soil clods and surface roughness and develop parameters for designing machines to provide most effective soil surface conditions, and determine feasibility of treating clods with chemical and petroleum-based preservatives to resist disintegration.

-- Use landforming for wind erosion control: Determine influence of topography on wind erosion and develop engineering specifications and design criteria for landforming to control wind erosion.

-- Improve wind erosion control attainable from deep plowing sandy soils: Conduct research to establish minimum clay contents at reachable depths to provide control for extended periods at reasonable costs.

-- Predict impact of emergency tillage on total seasonal erosion: Evaluate various emergency tillage implements such as chisels, furrow openers, sandfighters, etc. for effectiveness and duration on soils of various textures and water contents.

-- Preserve and extend the wind erosion protection of crop residues: Study basic microbial activity, screen and test various commercial products with potential for residue preservation, and develop economical methods for using the technology.

EXPECTED BENEFITS

In Technical Objective 2, "Improved Wind Erosion Control to Protect Crops and Soils and Reduce Air Pollution," estimates show that annual benefits from visualized technology on wind erosion equal $146 million. Most of the visualized technology relates to tillage aspects of wind erosion control. Monetary benefits would accrue from reduced crop losses; additional acreage made available for economic return; improved soil productivity from lessened erosion; more nearly accurate current and future commodity pricing because of improved accuracy in estimating damage and forecasting food supplies; reduced maintenance of roads, fences, and irrigation and drainage ditches; and reduced damage to mechanical and electrical apparatus from dust.

Health, accident prevention, improved environment and aesthetic factors by reducing dust and air pollution would benefit 12 million people and 36 million livestock in the Great Plains, with similar benefits to other regions where wind erosion is a problem.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE (MODELING)

Because a wind erosion equation (deterministic model) already exists and is used extensively, potential is excellent for interregional extrapolation of new technology. Benefits from new tillage technology that will reconstruct fine soil particles, produce a cloddy surface, increase surface roughness, and maintain residue on the surface can now be evaluated for wind erosion control. However, much research is needed to evaluate tillage requirements for the sundry soil, climatic, vegetative, and moisture variables.

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TILLAGE SYSTEMS

W. C. Moldenhauer[1]

The problems of soil erosion from agricultural lands with resulting sedimentation and sediment-borne pollutants and airborne marticulate matter are well recognized and well documented. (See the Wind and Water Erosion sections of this report.) Generally surface residue tillage systems are more desirable than moldboard plowing mainly because they reduce soil loss. The problem for many years has been getting farmers to change and adopt surface residue systems. Reasons, whether real or imagined, include the following: (1) reduced temperature slows germination and early growth; (2) plow-disk-harrow is a proven, fast system; (3) full line of machinery is not available for many of the residue management systems; (4) machinery conversion costs money (all tillage machinery may have to be converted at once); (5) appearance of the surface residue field causes the neighbors to talk; (6) habit; farmers know how to handle their old, reliable system and resist change; (7) fear of unknown catastrophies--poor stand, diseases, insects. All have heard stories of big failures. We have to distinguish between reasons and excuses. We also have to be sure we are not encouraging a farmer to accept a system that will put him out of business.

Attitudes are better now than ever before for adoption of surface residue systems. The four principal reasons for this are erosion control, timeliness, energy conservation, and tilth improvement.

Erosion control.--In the past, few farmers talked about erosion; now everybody is talking. The reason is easy to understand--they are being forced by legislation to control erosion. A change of tillage is much simpler and cheaper than the alternatives (terracing, leveling, grading).

Timeliness.--Farmers have limited time to get their crops in (10 working days). We have a good case for surface residue systems, especially when farmers can't get fall tillage done. Usually in those cases, it is better to do nothing or do the minimum in the spring just before planting. Farmers will even sacrifice a little yield for timeliness.

Save energy.--This can be a significant factor where zero tillage works.

Improvement of tilth.--Farmers worry about compaction, tilth, and a gradual decline in productivity. They want to do what is right. If residue mixed into the surface a few inches is the answer, many will do it. We must capitalize on the general willingness of farmers to at least talk about and think about changing tillage. Research is needed to develop the best possible system for each soil type in the North Central Region.

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Tillage research has been going on in both ARS and State experiment stations at a number of locations in the North Central Region for a number of years. Tillage research for control of wind erosion and for moisture conservation has been done by ARS at Mandan, N. Dak.; Scotts Bluff, North Platte, Alliance, and Lincoln, Nebr.; Manhattan and other locations in Kansas; and Brookings and Madison, S. Dak. Tillage research for control of water erosion has been done at Columbia, Mo.; Ames and Clarinda, Iowa; Morris, Minn.; Lafayette, Ind.; LaCrosse, Wis.; and Coshocton, Ohio. Notable state centers for tillage have been Wooster, Ohio, Dixon Springs, Ill., Madison, Wis., and Waseca and Lamberton, Minn. Present locations for ARS work are Mandan, N. Dak., Lincoln, Nebr., Madison, S. Dak., Manhattan, Kans., Morris, Minn., Ames, Iowa, Columbia, Mo., Lafayette, Ind., and Coshocton, Ohio.

Combined state and ARS research over the North Central Region gives a picture of which of the surface residue systems give satisfactory yields on the various soil types. Summarizing these voluminous results generally, we find that most surface residue systems are adaptable to medium-textured, well-drained soils. The northern part of the Corn Belt has more severe, early spring temperature stress than the southern part. In this northern area, which includes northern Indiana, northern Illinois, Iowa, Minnesota, Nebraska, and South Dakota, mulch should not cover the row area (Allmaras and Nelson, 1971). While presence of mulch does not give a consistent increase in yield in the northern Corn Belt, it does in Ohio (Van Doren and Triplett, 1973) on well-drained, medium-textured soils. They found most tillage and mulch effects to be additive. Results from Ohio, Indiana, and Illinois show lower yields for residues compared to clean tillage on dark-colored, poorly drained soils. Till planting was found to give highest yields of corn (following corn) in such divergent areas as South Dakota (Olson and Schoeberl, 1970) and Indiana (Giffith and others, 1973). In Indiana, till planting was done on a ridge formed during corn cultivation. More favorable early season temperatures resulting from planting on the ridge may have been responsible for the higher yields from till planting compared to other tillage systems. Griffith and others state that, "in general, as amount of tillage decreased and percent ground cover increased, plant growth was slowed and maturity was delayed in northern and eastern Indiana. These same factors had a positive effect on growth on the southern Indiana soil." They also state that, "till planting may also be competitive on fine-textured, poorly drained soils if used in conjunction with pronounced, residue-free ridges to achieve better drainage, thus improving warming and drying." Behn (1973) reported success on the poorly drained, Webster, silty clay loam soil of Iowa using residue-free ridges and planting with a till-planter.

Moldenhauer in preliminary (2-year) unpublished data from Madison, S. Dak., and Lamberton and Morris, Minn., confirmed the yield advantage for till plant for corn following oats at Madison. Oats showed a definite yield increase for moldboard plowing over unplowed cornstalks at Madison and Morris. Soybeans after corn yielded lowest on no-till but were close to plowing for other surface residue treatments. Yields of corn following soybeans were highest for fall chiseling and lowest for plowing at Morris. At Lamberton they were highest for plowing and lowest for no-till, with chiseling near the

lowest yielding and strip rototill near the highest. Illinois results from Catlin and Flanagan silt loams (Oschwald and Siemens, 1976) show little difference in corn and soybean yields between fall plowing and such surface residue tillage as chisel, disk-chisel, and coulter-chisel. Chop-plant corn yield was lowest on the Catlin but next highest on the Flanagan silt loam. Planting corn in killed sod has given satisfactory results in Ohio, Missouri, and southeastern states.

The foregoing show that some form of surface residue tillage system can be adapted to well-drained, medium-textured soils throughout the Corn Belt, which is important because these are generally the soils with greatest erosion by water. Wind erosion, however, can and does occur on flat, poorly drained soils as well as on sloping, well-drained soils. This type of erosion is a serious and recurring problem in the western part of the North Central Region and on sandy soils everywhere in the Region.

Surface residue tillage is, of course, an effective control measure for wind erosion. The problem in the western states, especially where summer fallow is practiced, is to keep enough residue on the soil surface at all times to control erosion effectively. Both tillage and drought are factors in reducing available surface residue (Fenster, 1973). Past research has concentrated on complete, chemical weed control where residue was not disturbed over the entire 14-months' fallow and as little as possible during the fall and winter of the establishment period. Maintenance of surface residue over this long period is especially difficult in spring wheat areas (Fenster, 1973). Weed control is more difficult when residues are maintained on the soil surface. Fenster (1973) reports that larger machinery and more powerful tractors have helped time weed control. Residue saving operations such as rodweeding can be better handled with the larger tractors. Large combines must have straw spreaders to keep straw from bunching.

Fenster feels that advances have been made recently. Good stubble-mulch farming can be performed with herbicides alone or in combination with tillage. Present herbicides, however, are too expensive and may have residueal effects. The advent of more desirable herbicides will be a great help to tillage systems for control of wind and water erosion in the Great Plains.

Some tillage work for wind erosion control is going on in the Red River Valley of Minnesota and North Dakota. Surface residue tillage has not been popular, especially on the Fargo clay soils, because of severe temperature and wetness problems in the spring. Some preliminary work has been done with a strip-rototiller in wheat stubble and incorporating herbicides in the fall to be planted to sugarbeets in the spring. Interest has even been shown in fall planting of coated sugarbeet seed.

RESEARCH NEEDS AND APPROACHES

Research effort is needed to adapt surface residue tillage systems to the dark-colored, poorly drained soils in the Corn Belt. Some effort has gone into developing ridge planting and multiple row bedding, but much more needs to be done. Research is needed to make surface residue systems more effective

for erosion control on sloping soils by reducing runoff. Oschwald and Siemens (1976) show impressive (five to ten-fold) reduction in soil loss by their surface residue systems but only a 35 percent reduction in runoff. On long or steep slopes, runoff water may wash off the mulch or undercut it, causing excessive rill erosion. Design systems using combinations of surface mulch and stirring will cut down the runoff water available for erosion. Finally, entomologists, plant pathologists, and plant breeders, as well as soil and weed scientists, agronomists, and agricultural engineers, must get involved in research with surface residue systems in the Corn Belt. Agricultural scientists have made the conventional tillage system preeminently successful. A similar commitment is needed to making surface residue systems work as well.

Better herbicides seem to be the answer to wheat-fallow problems. Equipment problems and procedures seem to be well worked out. Tree shelter belts seem to be a problem in drier areas but are certainly an area of research for the Red River Valley and sandy areas of the mid and eastern Corn Belt. Fall strip tillage in wheat stubble for sugarbeets and even winter planting to avoid delays in the spring should get attention in the Red River Valley. Spring strip tilling in wheat stubble for sugarbeets needs research in western Nebraska.

EXPECTED BENEFITS

The principal benefit of surface-residue, tillage systems is in control of soil erosion and, thus, reduction of sediment and sediment-borne pollutants and air-borne particulate matter. Research on improvement in yield will make the systems more desirable to farmers. Research in improvement of erosion control capabilities of the systems will make them more desirable and more satisfactory as erosion control measures. The pressure on ARS, the Soil Conservation Service, and the Extension Service to come up with acceptable erosion control systems is very real. Evidence shows that surface residue tillage is the practice farmers have chosen as the most desirable of the alternatives (or the least offensive). We must recommend systems that have the least risk of proving disastrous to production. We must bend our efforts toward developing systems that are as reliable as the ones farmers are now using.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

There are three dependent variables that must be quantified and that can be predicted using a model. One is soil loss, one is water loss, and one is yield. Water loss is positively or negatively related to yield within each year; soil loss is related to yield only over years (except in extreme cases), not within years. We have a model for soil loss (the Universal Soil Loss Equation) into which the soil loss variable of tillage could be made to fit. A water loss model is conceivable. Yield must necessarily be placed within a plant growth model, of which there are several available.

To approach these as three separate models seems reasonable. Then, if there is a reason for doing so, they could be combined later. The soil and

water loss models are likely interrelated to the extent that they should be combined.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

Most of the data needed for a first approximation of the foregoing three models is available. Some work has already been done by Wischmeier (1973) on adapting the Universal Soil Loss Equation to tillage system effectiveness. A project underway at Purdue Univesity (using a procedure developed by Swartzendruber, 1974) should have significant input into a runoff model. The greatest need is to find a modeler to develop the framework. Once this is done, needed inputs can be solicited from researchers now working either for ARS or Cooperative State Research Service. Effectiveness of the modeling effort will depend on the SMY's assigned to it and the effectiveness of the cooperation between the modeler and the field research scientists.

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ENERGY REDUCTION

J. M. Laflen[1/]

Energy in agriculture continues to be the subject of numerous reports. Most reports indicate that Unites States agriculture uses less than 4 percent of the total U.S. energy. Many recognize that there are various strategies that could be followed in meeting U.S. food energy and protein needs, with a lower input of cultural energy. (Cultural energy as used here is all energy used in production, except solar energy, supplied to a growing crop or animal.) However, technology, in the form of improved animals, crops, machines, and so forth, is expected to produce the diet that U.S. citizens prefer, at a lower energy usage. Within this section, the emphasis will be placed on potential energy reduction in crop production. Corn will be used as an example.

A typical energy budget for corn production is given in Table 1. Data used are from several sources and could have been selected from several others without gross changes in the stated energy requirements. About 25 percent of the energy in corn production is required for mechanical operations and the building and repairing of machinery for the mechanical operations, whereas nearly half the energy is in fertilizers. A little over 20 percent of the energy for corn production is used in drying corn. Only about 3.5 percent of the energy for corn production is used in pesticide manufacture and distribution.

SOME MAJOR ALTERNATIVES IN ENERGY REDUCTION

Some major alternatives in energy reduction for corn production are (1) reducing cultural operations, (2) reducing nitrogen fertilizer use, and (3) reducing energy requirements for drying. Others could be considered, but some of these, such as removing poorest quality land from crop production, could involve substantial changes in the structure of farming.

Reducing Cultural Operations

The potential for reducing cultural operations has been discussed by several authors. Wittmuss and others (1975) compared energy inputs for several corn production systems. They found that minimum tillage might substantially reduce cultural energy requirements for corn production. Heichel (1976) also found that minimum tillage might substantially reduce energy requirements, particularly if yields could be maintained. Nelson and Burrows (1974) indicated that no-till corn production would reduce fuel requirements, but yields would be reduced so much that in terms of the ratio of energy produced

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to energy used, no-till would not be preferable. In a recent Council of Agricultural Science and Technology (CAST) report (1975), reduced or no-till systems, while reducing on-farm fuel usage, might actually increase total energy usage. In any case, not all land is suitable for systems of reduced tillage.

Reducing Nitrogen Fertilizer Use

Heichel (1975) suggested that because of transportation and application energy requirements, manure for fertilizers is not possible when the application site is not within a 3-mile radius of the feedlot. Pimentel and others (1973) indicate a potential energy savings of 1.1 million kcal per acre when a feedlot is within 0.5 to 1 mile of the field. They estimated that the manure supply was sufficient to fertilize 30 percent of the 1970 harvested corn acreage, but when manure was to be used to fertilize cropland, redistribution of livestock facilities would be required. This would also require a careful analysis of associated costs.

A CAST report (1975) indicates that substantial increases in efficiency of fertilizer use could be achieved by application of technology available now. Soil tests are not used to the degree necessary to select application rates. Nutrients are not applied at the optimum time and may not be placed at the point where maximum benefit is achieved. However, costs in energy may be associated with optimizing fertilizer use. Optimum timing of application may require additional trips over the field and may reduce timeliness of other operations, thereby reducing yields. Good placement may require more energy and more equipment.

Reducing Energy Requirements for Drying

Using substantial amounts of cultural energy for crop drying is a relatively recent development. Solar energy, usually applied as the crop stood or laid in the field, has been the predominant energy source for lowering moisture content of crops to a safe level for storage until recently. Research is underway to replace with solar energy the cultural energy presently used to dry agricultural produce.

One factor in the move to cultural drying of grains was the development of machinery that would harvest grain, particularly corn, at a high moisture content. Corn that was picked and stored in naturally ventilated cribs required little cultural energy for drying. Corn pickers require less energy for manufacturing than combines, but their capacity is substantially less. Storage for ear corn may require more energy for construction than storage for grain. Energy requirements for hauling ear corn and disposing of the cobs after shelling need to be taken into account. Increased crop loss needs to be considered, but improved grain quality could result.

Alternatives in crop production that result in a major decrease in cultural energy requirements exist. All have some impact upon tillage because they affect how crops are grown, but reducing cultural operations has the most

impact upon tillage. All listed above require extensive analysis before implementation. All affect an entire farm. Several could have a regional or national impact on agriculture.

RESEARCH NEEDS AND APPROACHES

Reducing Cultural Operations

A major research and development effort is needed in the Corn Belt to determine the soil and climatic conditions where conservation tillage can be used in corn and soybean production. Production potentials for the various soils, climates, and systems need to be determined. Potential pests must be determined, and effective control methods developed. Varieties must be adapted for best performance under conservation tillage conditions. Economic analyses for system management must be made. Machinery for planting and performing cultural operations needs to be adapted or developed.

An interdisciplinary team approach is needed. Areas should be set aside as conservation tillage research and demonstration sites for evaluation of tillage systems. Pest problems should be monitored. Varieties should be evaluated and tillage machinery tested. Primary emphasis should be on no-till systems because these require the least energy for production and have the lowest power requirements.

Energy-Efficient Farming Systems

Farming has changed drastically over the decades, almost always toward a greater use of cultural energy. ARS should establish a center for the analysis of farming systems. The center should be charged with developing criteria for farm operation (including sizing and operating rules) under various energy usage levels and the capital and management levels expected. An important part of the center research should be directed toward the strategies required to preserve the family farm and to establish, or reestablish, the family farm in many areas. Strategies developed would include both on-farm strategies and the legal, economic, and institutional strategies needed.

For example, the center might study the prospect of eliminating artificial drying of corn. This would, perhaps, involve the harvest, storage, handling, and sale of ear corn. The prospect of using legumes in rotations, and the farm required to do this, could be studied.

Multidiscipline teams of agronomists, animal scientists, engineers, economists, and mathematicians would be required.

SUMMARY

Major reductions in energy use in crop production can be effected by reducing cultural operations. The development of crop production systems under no-till conditions, or minimum tillage conditions, should be the objective of a major coordinated research effort.

ARS should establish a center for the analysis of farming systems. The center would study and develop energy-efficient farming systems and analyze their impact on the farm and on society. The center would also develop strategies for preserving, establishing, or reestablishing the family farm.

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Table 1.--Typical energy requirements (kcal/acre) for corn production

Operation	Manufacture + Repair + Tires	Fuel	Total	Percent of total
Plow[1]	80,500	445,400	526,000	8.3
Disk[2]	50,500	132,300	182,800	2.9
Plant[1]	82,200	115,000	197,200	3.1
Cultivate[1]	31,400	58,300	89,700	1.4
Spray[1]	17,100	24,300	41,400	0.7
Harvest[3]	117,600	216,000	332,600	5.3
Chop stalks[1]	38,500	123,100	161,600	2.6
Pesticides			224,000	3.5
Fertilizers			3,162,500	49.9
Drying			1,415,400	22.3
Total			6,333,100	

[1]Clark and Johnson (1974).

[2]Based on Clark and Johnson offset disk, except fuel cost taken from extension publication (Constein, undated).

[3]Estimated. Based on combine of 33,000 lbs., energy of manufacture estimated at twice that for a tractor given by Clark and Johnson. Life based on ASAE estimate (2,000 hrs), estimated acreage based on 4 mph, 6" to 30" rows. Repair based on ASAE data. Fuel taken from extension publication (Hull, 1974).

Pesticides: 2.4 lb/A Atrazine, 0.5 lb/A 2-4D; 36,532 BTU/lb of 2-4D, 85,660 BTU/lb of Atrazine. Data from Green (1975).

Fertilizer: 120 lb/A N, 37.5 lb/A P_2O_5, 25 lb/A K_2O; 25,000 BTU/lb N, 3,000 BTU/lb of P_2O_5, 2,000 BTU of K_2O (White, 1973).

Drying: 100 bu/A at 6.5 bu/gal of LP gas to remove 10 percent moisture content.

TILLAGE MACHINES

D. C. Erbach[1]

NATURE, SCOPE, AND SEVERITY OF THE PROBLEM

Mechanical tillage is the most commonly used direct method of altering the soil conditions that affect plant growth and soil and water conservation. Nearly all cropland in the North Central Region is tilled at least once for each crop that is grown and most is tilled more often. If planting and wheel traffic are included, all cropland is mechanically distrubed several times each year. There are many machines available for tilling soil, and a large expenditure is made annually for tillage equipment and for operation of that equipment.

Traditionally, tillage has been considered an art. Most tillage systems have been developed by trial and error and many of the soil-engaging tools presently used have been developed through a process that involves "blacksmithing" metal into a shape that is thought will perform a desired function and then field testing and modifying the tool until performance is satisfactory. Much has been learned, through research and practice, that can be used to design tillage tools with decreased draft, increased life, and increased reliability.

Considerable information is also available for designing tools to physically move soil and to cover plant residue and for design of traction devices to pull tillage machines. Much less is known about designing tools to modify soil conditions to improve plant growth and about selecting the tillage operation that should be performed to create the soil conditions most desirable for production of a given crop.

The major problem in tillage tool development is knowing and being able to define when performance is satisfactory. The optimum soil conditions for crop growth are not well defined nor are the effects of deviations from the optimum well understood. This is largely because there are no practical techniques for measuring, or methods for describing, most soil conditions important for crop growth.

The variability of soil and the complexity of the relationships between machines and soil and between soil and plants have hindered development of criteria for tillage machine performance and design. However, if tillage is to become a science and significant advances are to be made in design and selection of tillage tools to perform only that tillage necessary to create the desired soil conditions, these performance and design specifications must be developed.

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PAST AND PRESENT RESEARCH

Much tillage machine research has involved field comparisons of commercial and experimental equipment. These comparisons have been based on crop yields, root development, weed control, crop germination and emergence, plant stands, herbicide incorporation, surface plant residue, water runoff, soil erosion, fuel consumption, draft, and field efficiency. The work in the North Central Region has been mainly of this type. Much work has also been done on soil-tillage tool reactions involving forces on the tillage tool and wear of the soil-engaging components.

The effects of tillage on many soil conditions have been observed. Measurements of temperature, moisture, oxygen, mechanical impedance, surface roughness, bulk density, aggregate size distribution, aggregate stability, porosity, pore size distribution, and other factors have been made. By far the most information has been collected on soil temperature. That is because temperature transducers and associated instrumentation are well developed. Instrumentation and techniques for measurement of most soil factors are inadequate to obtain data that can be used to relate plant response to tillage-induced changes in soil factors.

Also some theoretical work has been done on soil structure and aggregation and its effect on diffusion of water, air, and heat.

RESEARCH NEEDS AND APPROACHES

For improving tillage machines, the most important research need is to develop techniques for measuring important soil parameters so that the soil condition at a given time may be described. The description of soil conditions must be in terms that are important for crop growth, pest control, and soil and water conservation. Also important is to monitor the change in soil condition with time.

Because soil conditions, especially in the field, are highly variable, there is need for a probabilistic technique for describing the condition of individual soil factors and for combining this information into an adequate description of the overall soil condition that can be related to tillage tool operation and to crop response.

As measuring and describing soil conditions becomes possible, to understand how soil conditions after tillage are affected will become possible by passage of tillage tools of various configurations, operated at different speeds and depths, in soils of different types and at different initial conditions. This information, combined with knowledge of the desired soil conditions, can be used to develop design and performance criteria for tillage machines.

Assuming the entire complex, including soil type, soil condition, tillage tool configuration, and tillage machine operation, could ever be fully understood and described may be idealistic. However, unless information of this type is obtained, tillage will remain an art, and tillage tool development will continue to be cut and try. Progress toward obtaining the optimum soil

condition for crop growth, pest control, and soil and water conservation with the minimum tillage input will then be slow.

EXPECTED BENEFITS

The benefits that can be expected from the use of tillage machines developed to till only the amount and in the manner necessary to change the soil conditions to those desired for optimum crop growth, pest control, and erosion control are:

1. Increased production. When the soil environment is a limiting factor for gemination, emergence, or growth of the crop, an improvement in soil conditions will improve crop development and will result in higher yields. Yields will also be increased by manipulation of the soil to decrease yield-limiting competition from crop pests. An example would be to manipulate weed seed distribution in the soil to control weed germination. Improved water infiltration and decreased water evaporation will increase yields under moisture-limiting conditions.

2. Increased production efficiency. Machinery requirements and labor and fuel inputs will be decreased by eliminating unnecessary field operations and by use of more efficient tillage machines.

3. Decreased soil erosion. Use of tillage to properly control soil topography and plant residue distribution will protect soil from wind and water erosion.

The magnitude of potential benefits from improvements in tillage machines is great when it is considered that (1) there is an estimated annual expenditure of $500 million for new tillage equipment and in excess of $1 billion for new tractors (their major use being for tillage) and (2) approximately one billion gallons of fuel are consumed annually for tilling the 190 million acres of cropland in the North Central Region.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

Improved techniques for measuring and describing soil conditions and for predicting the change in soil conditions caused by passage of tillage tools through soil could be applied universally to crop production systems. The techniques and information would be useful for modeling soil-machine systems and for improving design and operation of tillage machines. The information obtained would also be useful for modeling of crop production, pest control, and erosion control systems.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

A team of scientists from several locations in the North Central Region is needed to work cooperatively toward (1) determining what soil conditions are important for crop growth, pest control and erosion control; (2) determining how to measure and monitor important soil conditions; (3) determining how tillage may be used to control these conditions; and (4) establishing tillage machine design and performance criteria. This team should include specialists in plant growth, soil science, soil mechanics, instrumentation, pest control, erosion control, and tillage equipment.

At some locations in the North Central Region, a laboratory with soil preparation and handling equipment, with a plant growth facility, and with instrumentation for measuring soil conditions is needed for investigating the changes in soil conditions caused by tillage and the plant growth response to soil conditions created by tillage and planting equipment. The facility is needed so that specific and repeatable soil and environmental conditions can be obtained.

TILLAGE AND HYDROLOGY

C. R. Amerman[1]

NATURE AND SCOPE

Hydrology is the study of the occurrence and movement of water in and on the earth's crust. A major control on the various hydrologic mechanisms is the earth's surface. The soil surface, that is, the soil-atmosphere interface, is essentially a divider. The hydrologic mechanism of infiltration operates at this surface and determines what portion of precipitation is directed into the soil for future evaporation, transpiration, and accrual to ground water.

Precipitation in excess of infiltration runs off. Restrictions on its movement over the surface are few, and flowing water tends to concentrate in channels and reaches relatively high velocities. The potential is high for various sorts of damage, the most prevalent of which is erosion.

The soil surface and materials residing upon it also influence the rate at which soil water evaporates and is thus lost from the soil water reservoir.

Man's manipulation and treatment of the soil surface influences infiltration and evaporation and therefore other parts of the hydrologic mechanism. Let us define tillage as the manipulation of the upper few inches or feet of soil for agricultural purposes. Such manipulation can range from that accomplished with deep plows and chisels to compaction by tractor tire during broadcast seeding. On the microscale, tillage or the lack of it increases or decreases local infiltration. On the macroscale, however, tillage is only one part of a farming or land treatment system or practice. Other parts of the practice such as direction of tillage, surface cover, and use of such water control devices as terraces or meadow strips may reduce or magnify the effects of tillage. Increasing the scale still further, the downstream effect of a particular field subjected to a given agricultural practice will depend upon the position of that field in relation to other farmed or unfarmed areas in the same drainage basin and upon the hydraulic characteristics of the drainage system to which it contributes.

Time is a factor influencing the magnitude of tillage effects. As soon as the tillage operation is finished, the disturbed soil zone starts to return to the untilled state.

Antecedent moisture conditions influence infiltration also. To consider the extreme, when the whole soil system is near saturation as may happen in late winter and early spring or after prolonged rainfall in any season, the soil has little room to store more water, and the hydraulic gradients are such that the speed with which water can move downward through soil is low. During

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such times, infiltration is likely to be low regardless of soil surface treatments.

PAST AND PRESENT RESEARCH

A wide variety of tillage methods and other surface treatments has been tested on runoff plots and small watersheds. In recent years, much interest has focused on various forms of minimum tillage, including no tillage. Bertrand and Mannering (1963) used a sprinkling infiltrometer on plots somewhat larger than 1 m^2 in area to show that minimum tillage results in higher infiltration rates than conventional tillage if a crust is now allowed to form. Crust formation reduced infiltration rates by 50 percent. Sloneker and Burwell (1976) also used a sprinkling infiltrometer to test several tillage methods. They observed that tillage increased infiltration and also observed that soil cover, which retards crust formation, increases infiltration even more.

Free and Bay (1969) reported a nine-year plot study of conventional, mulch, and plow plant tillage. There was little difference in the total runoff from the several treatments during the dormant season. During the growing season, the rough surface resulting from plow-planting yielded less runoff than the other treatments. Differences were statistically significant at a level unspecified by the authors. Using a large rainfall simulator, Meyer and Mannering (1961) had shown essentially similar results for the periods immediately following planting and cultivation. Moldenhauer and others (1971), using a large rotating boom rainfall simulator in early June, found that runoff varied from lowest to highest in the order row plant, conventional tillage, and ridge tillage. The differences were not significant at the 5 percent level.

Onstad (1972) compared several tillage requirements on 0.01-ha plots and found that growing season runoff varied from high to low in the following order: fallow, conventional, mulch, till plant up- and down-hill, and till plant across the slope. There was statistical significance at the 1 percent level only between conventional tillage and till planting across the slope.

Comparisons between no-tillage and various types of tillage treatments have resulted in differing conclusions regarding runoff influences. For a single storm in early June, Harrold and Edwards (1972), observing small watersheds of near 0.6 ha in size, found slightly more runoff from no-till as compared to clean till when both were on the contour. Over a three-year period, however, Harrold and others (1967) observed that no-till runoff on small watersheds was only about one-third that of conventional tillage. This was a dry period, however, and runoff for both practices was quite small. Shanholtz and Lillard (1969) observed from 3 to 4 times more runoff from conventionally tilled 6-m square plots than from no-till plots of the same size. McGregor and others (1975) observed that, on plots and small watersheds, no-till corn after beans yielded more runoff than conventionally tilled beans. In both these comparisons, the rows ran up- and downhill.

Shanholtz and Lillard (1969) also observed that soil water content persisted at higher levels longer under no-till than under conventional tillage,

but eventually dropped to a lower level than conventional tillage during a prolonged drought period.

Ehlers and van der Ploeg (1976) observed soil water conditions for four years under conventional tillage and no-till conditions. They noted that unsaturated but wet (suction < 100 cm water) hydraulic conductivity was higher in untilled than tilled soil. They concluded that large pores are broken up in tilled soil but remain continuous in untilled soil. However, they did not detect a significant difference in the treatments as regards rates of evaporation and drainage.

Greb and others (1970) observed that increasing amounts of soil water storage occurred under increasing depths of mulch with stubble mulch tillage. Army and others (1961) showed that chemical weed control is also effective in improving soil water conditions but that this effectiveness does not extend below 1.0 cm. Unger and others (1971) compared a variety of tillage-mulch-herbicide combinations and found that cultivation without herbicide limited profile water additions to the upper 75 cm, but herbicide treatment with or without cultivation resulted in profile water additions on down to about 120 cm.

Musick and Dusek (1975) studied the effects of deep tillage on Pullman clay loam under irrigation. Increasing tillage depth to 40 cm increased infiltration rate, but deeper tillage caused no further increase. Deeper tillage led to greater deep percolation losses than 40-cm tillage, however. Tillage to 40 cm resulted in higher infiltration rates in subsequent years when normal tillage to 20 cm was practiced. Sandoval and others (1972) investigated tillage depth effects on a sodic claypan soil and found that 30- to 60-cm tillage depths when compared to 15-cm normal depth of tillage resulted in greater water storage at the end of a fallow period, particularly in the 60- to 90-cm depth. The differences, however, were quite small.

The above papers and many others of a similar vein present essentially microscale results. These results are quite important from an agronomic standpoint and give insights on the development of surface treatments for efficient utilization of precipitation and irrigation water for crop production. However, one cannot generalize from the microscale to the macroscale, from small plots to watersheds. Edwards and others (1973) studied a 28-year record for watersheds in the size range 0.7 to 3.2 ha. These watersheds were in corn, wheat, meadow, meadow rotations under either conservation (contour and contour strip cropping) or nonconservation (rectangular fields without contouring or strip cropping) management. Conservation practices reduced growing season runoff by about 50 percent and peak rates of flow by about 33 percent. McGuinness and others (1971) commented that downstream effects of any treatment on any given area are likely to be well masked by the hydrologic activity of other areas (meadows, woodlands, or other treatments) within the same watershed. For watersheds from 12 to 120 ha in size, Harrold and others (1962) could not detect statistically significant differences in either volumes or peak rates of runoff when comparing conservation and nonconservation water sheds. Even reforestation of a 17.2-ha watershed did not cause an apparent reduction in peak flows during major storms, although annual and seasonal runoff volumes were considerably reduced. These watersheds, in contrast to

the single cover watersheds studied by Edwards and others (1973), had considerable areas in permanent pasture and woodland and, in general, were characterized by incised channels and base flow.

Considering relatively small watersheds of less than 80 ha, Baird (1946) showed that a conservation farming method yielded less runoff than a nonconservation method. He found that peak rates were reduced by a nearly constant amount, regardless of size of storm.

Sharp and others (1966) attempted to determine the effects of land treatments on large river basins (hundreds of square kilometers in size). They tried several statistical techniques of greater or lesser sophistication and could not detect, among other things, even the influence of a number of reservoirs. Kennon (1966), however, was able to detect a 20 percent reduction of streamflow for a 221 km^2 basin, 75 percent of which was controlled by reservoirs. Kuzin (1965) strenuously objected to the extrapolation of plot and small watershed data to river basins when L'vovich (1960) attributed reduced flows in the Don River to increased cultivation within its basin.

In summary, the literature indicates that the detection of tillage effects on hydrology is largely a matter of scale. Even on the scale of small plots, researchers are having difficulty measuring rather small differences in runoff and agreeing on whether the differences are positive or negative. As larger areas are considered, a multitude of such other factors as field position, drainage system hydraulics, and so forth, apparently overpower not only tillage influences, but also farming practice effects.

RESEARCH NEEDS AND APPROACHES

Considering the circumstance that hydrologic effects of cultural practices can hardly be detected on large, mixed cover watersheds, the practical significance of tillage effects on hydrology per se seems to be limited to the field or small watershed scale, at most. This observation does not necessarily extend to the detection of such waterborne substances as sediments and dissolved chemicals.

On the smaller scale, hydrologic effects of tillage may be quite important, particularly as regards its influence on the efficient use of irrigation water or precipitation by crops, maintenance of an adequate rooting depth of soil, and the management of fertilizers and pesticides.

After a brief review of only a sampling of the tillage literature relating to infiltrometers, runoff plots, and small watersheds, one is struck by the heterogeneity in results and the seeming impossibility of drawing clear-cut conclusions on the basis of the data alone. This may in part be due to the "lumped system" nature of most plot and infiltrometer studies of runoff response to tillage and to the uniqueness in experimental design for each tillage study. Runoff from a plot is a function of many factors besides tillage. Slope, aspect, subsurface physical and hydraulic conditions, soil and vegetation characteristics, plot borders and observational equipment, and climatic factors all interact with the particular tillage treatment to

influence runoff. To begin to get a handle on hydrologic influences, the problem must be broken down into a number of parts and a research approach developed for each part.

From a hydrologic standpoint, a soil surface may be characterized by its infiltration properties and by its microtopography. Below the surface the soil is hydrologically characterized by its soil water pressure head and hydraulic conductivity properties as functions of water content. Other characteristics, such as slope, the presence of impeding layers below the tilled zone, mulches, and crop canopies are environmental or boundary conditions. The hydrologic impact of tillage is really the impact on hydrologic properties of the interaction of tillage with a soil of given initial character and with given boundary and environmental conditions.

Definitive study of the characteristics discussed may require even further subdivision of the problem. Consider infiltration, for example. Skaggs and others (1969) present infiltration equations due to Green and Ampt (1911), Philip (1969), Horton (1940), and Holtan (1961). The bases for these equations range from empirical to physical. Each equation contains terms relating to internal soil properties or to internal soil water conditions. Each equation also contains one or more parameters whose values must be obtained by fitting the equations to observed infiltration data. Without this fitting or calibration procedure, none of the equations can be applied to a field situation.

Considerable effort has in recent years been expended upon developing sophisticated numerical models to depict infiltration (Rubin, 1966; Whisler and Klute, 1967). These models suffer the same shortcomings as the infiltration equations in that they cannot depict soil surface conditions, and thus there is no way to differentiate between a cornfield and a forest.

Infiltration is classically defined as the movement of water across a surface. The physically based equations referred to above (Green and Ampt, Philip) and the numerical approaches model infiltration by considering the physics of water flow in the soil below the surface, that is, they indirectly approach infiltration by modeling one of the boundary conditions to infiltration.

From the preceding, the reader realizes that no one, hydrologists, soil physicists, or tillage investigators, really understands infiltration. The same is true to greater or lesser extent of the formation of microtopography, and the in-soil establishment of the relation between soil water content and hydraulic conductivity and soil water pressure head. No one understands how a soil's phyusical constituents and chemistry interact with water, air, and organic life to give a particular dynamic expresion of these characteristics.

There will be argument over how fundamental we have to get in seeking understanding. I submit that we have to go deeply enough to develop mathematical expressions for the characteristics in which we are interested. With mathematical expressions as building blocks, we can construct simulation models and with good simulation models we can study tillage-soil impacts on hydrology at the desk with a minimum of field experimentation.

If simulation capabilities are not developed, then each new idea and combination of tillage methods will ave to be tested by large numbers of plots. For the same reasons that they now produce conflicting results, they will continue to do so. Furthermore, plot experiments take years, and farmers won't wait. A multiyear field experiment begun today runs a risk of producing information no longer needed by the time it is concluded. That risk will become larger as the rapidity of change in the agricultural sector continues to accelerate.

Based on the preceding observations of this section, I conclude that a portion of our hydrologic and tillage research effort should be devoted to development of knowledge leading toward the capability to simulate the hydrologic impact of tillage and/or of tillage-cropping-management systems on soils of given physical, chemical, and organic character. With the capability of soil-specific simulation, site or environmental and boundary conditions can be added to expand the capability to simulation of the hydrologic impact of tillage on given plots, fields, and watersheds. These capabilities would be a boon not only to the development of tillage-cropping-management systems, but also to increasing hydrologic simulation capabilities in general.

A possible approach is to assign a team consisting of a soil physicist, a soil chemist, and a microbiologist to perform an in-depth survey of the literature of their fields and of such allied fields as petroleum extraction technology, filtering technology, and so on. Their aim should be to pool their assembled knowledge in the development of a research plan with three objectives: (1) determine the physics of water movement across the soil-air interface and thus identify the pertinent hydraulic characteristics of such an interface, (2) determine how these surface hydraulic characteristics are established and controlled, and (3) determine how the hydraulic conductivity-soil water pressure head and the soil water content-soil water pressure head relations are controlled in soils.

At the end of an 18-month or 2-year period, the team should report their plan of research and be prepared to discuss experimental techniques, likelihood of success, and its probable cost in terms of dollars, facilities, and personnel. Feasibility of the plan can then be assessed and a decision made on whether to proceed in full, in part, or not at all.

Further outlining of the approach toward eventual simulation capability must await at least the aforementioned plan of fundamental research and assessment of its feasibility.

EXPECTED BENEFITS

Long-term benefits, as indicated in the preceding section, would accrue to tillage system development and assessment efforts and to the general field of hydrologic simulation. Tillage research and application would benefit primarily in terms of increased timeliness of the release of experimental results if a simulation capability is eventually obtained. The anticipated simulation capability would be a direct contribution to hydrologic simulation in general and would contribute to an increased capability for predicting downstream influence of various land use and land management plans.

POTENTIAL FOR INTERREGIONAL EXTRAPOLATION OF NEW TECHNOLOGY IN A PREDICTIVE SENSE

Simulation based on fundamental physical understanding will have no geographic limitations.

RESOURCES REQUIRED TO ACHIEVE RESEARCH OBJECTIVES AND GOALS

The most important resources are three team members well grounded in their own fields and in analytical mathematics. The team should be located at a university capable of offering extensive library facilities and technical backup in physics, mathematics, and chemistry.

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WEED CONTROL

L. M. Wax[1/]

Agricultural lands throughout the North Central Region are infested with a vast array of troublesome weeds. Annual grass and broadleaf weeds are most prevalent, but perennial species are present in many areas and are becoming much more troublesome in some cropping situations. These weed infestations cause loss of productivity by a variety of methods, but mainly by competition with desirable crop species for moisture, light, and nutrients. Weeds also harbor insects and diseases, hamper harvesting operations, and produce allergenic problems in humans. The extent of losses caused by weeds varies greatly with the location and situation but has been estimated to be about 10 percent of the total value of crop production, in spite of currently used control methods.

Many methods of weed control have evolved over the years, but until fairly recently, tillage in some form was the primary and most effective means of control. The development of modern, selective herbicide treatments for weed control has resulted in the replacement of some tillage with herbicides. But the most effective programs of weed control on much of the cropland involve a combination of nonchemical and chemical control. For example, in the North Central Region, most corn and soybean acreage receives one or more herbicide applications each year but, in addition, receives some form of preplanting tillage, mainly for weed control, and often a rotary hoeing and one or more sweep cultivations after the crop has emerged.

But tillage patterns are changing on our croplands, and in some instances, tillage may not play as important a role in crop production, and especially weed control, as it has in the past. The purpose of this paper is to discuss, in general terms, (1) some of the ways tillage has been involved in weed control in the past, (2) how it presently influences crop production with respect to weed control, and (3) research needs as tillage patterns change to meet the challenges of crop production in the future. The listed references should be consulted for a more specific review of the weed control aspects.

Reduction of losses caused by weeds in croplands from an average of 25 percent or more 30 years ago (some acres were unharvestable) to an average of 10 percent today has resulted largely from the development and use of selective herbicides. The evaluation, development, and use of these herbicide treatments have been, until recently, in systems involving conventional

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tillage. In row crops, this has usually involved moldboard plowing followed by several operations with implements such as the tandem disk to prepare a relatively smooth, firm, weed-free seedbed that is essentially free of surface plant residue. In this environment, proper selection of herbicides and application rates, combined with tillage after crop emergence, usually provides excellent and dependable weed control. However, certain practices in crop production are placing additional challenges on our developed systems of weed control. These practices include earlier planting of row crops, a move toward narrow rows in some crops, and minimum or conservation tillage, primarily for erosion control. These practices make weed control more difficult with conventional weed control systems, require new weed control practices, and shift the weed control program toward greater use and more precise application of herbicides.

By far the greatest use of herbicides in the North Central Region is for weed control in corn (Zea mays L.) and soybeans [Glycine max (L.) Merr.]. Most of these treatments are soil applications, as opposed to foliar, or post-emergence treatments. About half of the soil-applied treatments are applied to the soil surface prior to planting and incorporated (mixed) into the soil with various tillage implements. Some herbicides require immediate incorporation because they are volatile or subject to photodecomposition whereas others can remain on the soil surface for some time before soil incorporation without significant loss of activity. These preplant incorporated treatments, because they are not usually dependent on rainfall to be effective, are some of the most effective and consistent herbicides available for weed control. Examples of these are trifluralin (α,α,α-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) for use in soybeans and butylate (S-ethyl diisobutylthiocarbamate) for use in corn. For the most effective soil incorporation of these treatments, and similar ones, thorough mixing into the soil is needed to provide relatively uniform distribution both horizontally and vertically. Our studies, and those by other scientists, indicate that the most successful soil-incorporation procedure is to tandem disk twice, or to tandem disk once, followed by one pass with the field cultivator. Several other implements and combinations of implements provide adequate soil incorporation of these treatments as well. But those that provide good incorporation do not, in general, fit well into a program of reduced tillage. Tillage practices range from conventional to zero- or no-till, with many intermediate tillage systems, which in many instances have only omitted moldboard plowing and perhaps one seedbed preparation operation. The effective and consistent preplant incorporated treatments will not be available for the no-till acreage and on some of the intermediate tillage systems because the tillage required for incorporation is not consistent with the goals of conservation tillage. Thus, other herbicidal treatments are needed for these acreages.

Weed control in some of the intermediate tillage systems does not need to be changed markedly from that employed in a conventional system. Fortunately, studies are designed to answer these questions, and some answers are already available. The first change is normally the selection of herbicides that may be applied to the soil surface without incorporation as opposed to herbicides that require soil incorporation. For maximum effectiveness, these treatments are dependent on rainfall after application. Research results are not in agreement as to whether or not effectiveness of surface-applied herbicides is

reduced as increased amounts of plant residue remain on the soil surface. But in actual practice, both herbicide rates and spray volumes are normally increased as surface residue is increased to maintain the level of control normally achieved with application to weed-free and residue-free seedbeds. This additional difficulty with control has been attributed to the adsorption of herbicides on the residue, to the physical presence of the residue that may make coverage or incorporation more difficult, to the presence of large soil aggregates that may contain weed seeds that do not get early exposure to the herbicide, and to emerged weed seedlings that are not destroyed by tillage prior to planting.

Adsorption of herbicides on undecomposed plant residue remaining on the soil surface very likely does not play a very important role in reducing herbicide effectiveness. As less tillage is used, and more residue remains on the surface, the problem of emerged weeds at planting time is usually solved by the addition to the spray mixture of herbicides such as paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) or glyphosate [*N*-(phosphonomethyl) glycine] which have "contact" or "knockdown" activity on emerged weeds. Thus, with some modification in weed control procedures, primarily toward more dependence on herbicides, the producer has available satisfactory methods of weed control for most of the present intermediate tillage systems or those proposed for use in the near future.

Reduction of tillage operations influences herbicide residues in some instances. Herbicides such as atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-trizine], used for weed control in corn, may persist into the next cropping season occasionally and reduce yields of susceptible crops such as oats (*Avena sativa* L.) and soybeans. And herbicides such as trifluralin, used for weed control in soybeans, may on occasion persist into the next cropping season and reduce growth and vigor of crops such as grain sorghum (*Sorghum bicolor* L.) and corn. These problems do not normally occur in the North Central Region because these herbicides are usually decomposed to non-phytotoxic levels in the soil before the next cropping season begins. Degradation normally proceeds most rapidly under warm, moist conditions. Hence, the problems typically arise following seasons with cool, dry weather. In these situations, extra tillage, such as deep moldboard plowing, may be helpful in diluting the herbicide residues and helping to prevent a problem. In contrast, some of the more substantial herbicide residue problems have developed where the land was only chisel-plowed following a season which allowed only minimum herbicide degradation.

Zero- or no-tillage programs require major changes in weed control methods and for the most part involve total dependence on herbicides for weed control. Examples of these programs are no-till corn following sod, corn, or soybeans; no-till soybeans (double-crop) following small grain (mainly wheat [*Triticum aestivum* (L.)]; and the ecofallow program in the Great Plains. In the corn and soybean no-till programs, emerged vegetation is usually present at the time of planting. Thus a "contact" or "knockdown" herbicide such as paraquat or glyphosate is required to control existing weeds. At the same time, one or more other herbicides are normally applied to provide residual control of germinating annual grass and broadleaf weeds. And later, after crop emergence, postemergence herbicide applications may be needed to control weeds that escape

control with earlier treatments. For corn, a typical set of treatments may involve either paraquat or glyphosate plus alachlor [2-chloro-2',6'diethyl-N-(methoxymethyl)acetanilide] plus either atrazine or simazine [2-chloro-4,6-bis(ethylamino)-s-triazine], or both, at planting. Then, depending on need, such herbicides as 2,4-D [(2,2-dichlorophenoxy)acetic acid], dicamba (3,6-dichloro-o-anisic acid), or atrazine may be used postemergence. In double-crop, no-till soybeans, a set of treatments might involve paraquat or glyphosate plus alachlor or oryzalin (3,5-dinitro-N^4,N^4-dipropylsulfanilamide) plus metribuzin [4-amino-6-tert-butyl-3-(methylthio)-as-triazin-5(4H)one] or linuron [3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea]. Postemergence treatments, if warranted, might involve bentazon [3-isopropyl-1H-2,1,3-benzothiadiazin-(4) 3H-one 2,2-dioxide], naptalam (N-1-napthylphthalamic acid) plus dinoseb (2-sec-butyl-4,6-dinitrophenol), or 2,4-DB [4-(2,4-dichlorophenoxy)butyric acid].

Because cultivation between the rows after emergence is either very difficult or impractical in no-tillage systems, additional herbicide combinations and perhaps repeat applications must often be used to solve problems normally handled by cultivation between the rows. The cost of these additional herbicide treatments may more than offset the saving in tillage costs. However, the no-tillage system should have clear advantages in erosion control and energy savings.

Studies comparing weed control treatments in conventional, intermediate, and no-tillage systems indicate some definite problems for which solutions are needed. For example, certain weed species that normally germinate from only very shallow depths may become increasingly important when the soil is not tilled and these seeds are left on the surface. Fall panicum (Panicum dichotomiflorum Michx.) and crabgrass (Digitaria spp.) are examples in corn and soybeans and downy brome (Bromus tectorum L.) has become a serious problem when seeds are left on the soil surface in small grain areas of the Great Plains. Other species, such as common dandelion (Taraxacum officinale Weber) and burdock (Arctium spp.), normally no problem in cultivated fields, may become troublesome in the absence of tillage. Some of our most difficult-to-control perennial weeds with extensive root and rhizome systems, such as johnsongrass [Sorghum halepense (L.) Pers.], quackgrass [Agropyron repens (L.) Beauv.], yellow nutsedge (Cyperus esculentus L.), Canada thistle [Cirsium arvense (L.) Scop.], field bindweed (Convolvulus arvensis L.), common milkweed (Asclepias suroaca L.), and honeyvine milkweek [Ampelamus albidus (Nutt.) Britt.], thrive in the absence of tillage. Our most effective control of some of these species has been with a combination of preplanting tillage, preplanting incorporated herbicides, and postemergence cultivation. All of these methods of control are either eliminated or severely restricted by no-tillage systems. Fortunately, however, some new postemergence treatments such as glyphosate show tremendous potential for control of certain of these seldom-controlled species in no-tillage systems. Rotation of crops and proper selection of herbicide combinations to fit the existing weed problems will do much toward solving the challenges of weed control in reduced tillage situations.

New research approaches are needed to solve the challenging problems of weed control in the reduced and minimum tillage systems of the future. Some of

the more pertinent research approaches needed, as outlined in National Research Program 20280 - Weed Control, are listed below:

1. Investigate systems involving improved means of control of weeds in reduced- and minimum-tillage situations.

2. Develop improved means of control for hard-to-control annuals and perennials--evaluation of new herbicides, innovating uses of older herbicides, combinations, sequential treatments, application techniques, crop rotations, herbicide rotations, and using herbicides to control weed populations when they occur in crops that are tolerant to effective herbicides.

3. Investigate systems involving narrow-row soybeans to develop potential for increased yields in areas where narrow-row, weed-free soybeans outyield wide-row soybeans.

4. Develop improved means of application and placement of herbicides to improve crop safety, increase weed control, and reduce potential hazards to the environment.

5. Develop equipment and techniques for improving the precision and timeliness of herbicide applications and other control practices.

6. Investigate use of spray adjuvants to increase effectiveness of post-emergence sprays and reduce rates of herbicides required.

7. Investigate different techniques of seedbed preparation and soil management to develop methods for inhibiting or stimulating germination of weed propagules.

8. Integrate weed control techniques with other production and harvesting practices necessary in crop roations, conservation tillage, and double cropping.

Expanded research in the above-listed areas should result in many benefits. Some of the more obvious ones are summarized below:

1. Improve environmental quality through enhancement of chances for success in the use of conservation tillage practices.

2. Reduce losses in crop yield and quality caused by weeds and reduction of dockage costs caused by weed seeds in crop seed.

3. Reduce energy requirements for controlling weeds.

4. Reduce weed populations so herbicide use would be needed less frequently.

5. Improve control of resistant weeds with minor infestations to prevent spread and help to reduce future crop production losses and weed control expenses.

6. Improve use of water and plant nutrients and subsequently reduce energy in crop production.

The needed research would likely be more applicable throughout the North Central Region if it is conducted as a systems approach by two or three locations working cooperatively. At each location, active cooperative work is needed by teams of weed scientists, soil scientists, and agricultural engineers to research and develop integrated systems of crop production that maximize yields while emphasizing conservation tillage and judicious use of pesticides where necessary.

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